# THE SOIL UNDER SHIFTING CULTIVATION

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P. H. NYE

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D. J. GREENLAND

Technical Communication No. 51
Commonwealth Bureau of Soils
Harpenden

COMMONWEALTH AGRICULTURAL BUREAUX

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## PREFACE

Over 200 million people, thinly scattered over 14 million square miles of the tropics, obtain the bulk of their food by the system of shifting cultivation. They form a little under 10% of the world's population, and are spread over more than 30% of its exploitable soils. Up to a century or so ago shifting cultivation had no very serious effect on the farmland of the tropics, since the soil and vegetation were given adequate time to regenerate after a period of cropping. The comparatively recent influence of the European has led to much more intensive cropping of the soil. By abolishing the slave trade, suppressing tribal wars, improving the health of the people, and relieving famine, he has promoted a rapid increase in the population; and by creating a demand for export crops like cocoa, coffee and rubber he has increased the area under cultivation and reduced that available for subsistence crops. In consequence, vast areas of tropical forest and woodland have been transformed into less productive savanna grassland. This has led many to condemn shifting cultivation in the strongest terms: for example the staff of F.A.O. (1957) write "Shifting cultivation in the humid tropical countries is the greatest obstacle not only to the immediate increase of agricultural production, but also to the conservation of the production potential of the future, in the form of soils and forests". Yet, though primitive and apparently wasteful, when not pushed to excess shifting cultivation has for centuries given man his livelihood in the humid tropics; and it is significant that even now, after a quarter of a century of experiment in the African tropics, we have failed to introduce to the forest regions any method of staple food production superior to the system of natural fallowing used in shifting cultivation. On the contrary, failure to appreciate its nice adjustment to the tropical environment has led to many disappointments: Gourou (1953) rightly says "The disasters brought on by agricultural methods which have taken no account of the treasures of wisdom and experience accumulated in the old tropical system are a sufficient proof of the latter's value. It can be improved, but only if the reasons for its processes are fully understood".

Naturally, a practice that is so much a part of the social, economic and religious life of so many people has been studied in its many variants and aspects by a range of administrators, geographers, sociologists, economists and anthropologists; and among natural scientists by agronomists, foresters and plant ecologists. The soil scientist has, until recently, contributed remarkably little detailed information to this pool of knowledge, though he should have much

to offer, for it is the intricate relations between soil, fallow and harvest that so largely govern the ways of the people; and in turn, it is the people's practices that maintain or destroy the fertility of the soil. The reason for this neglect is partly that there have been few soil scientists working on native agriculture in the tropics, partly that before the war the prevailing attitude was to condemn the system of shifting cultivation and to seek to introduce a more European type of agriculture based on green manuring or mixed farming, and partly that the basic principles of soil science on which true understanding must be founded have only been formulated in recent years. The present attempt to analyse the effects of shifting cultivation on the soil has proved in fact a fascinating exercise in the application of these basic principles to a system of agriculture wholly different from the kind which stimulated their development in temperate lands.

In this account, an attempt is made to reveal those 'treasures of wisdom and experience' which, as soil scientists, we felt most at ease in seeking; and which have not received systematic treatment elsewhere. We have aimed in particular at a quantitative treatment, since this is the surest way of evaluating the many assertions about the effect of this or that factor on the fertility of the soil. We have not attempted to deal exhaustively with the mass of descriptive literature from all parts of the tropics giving details of the great variety of local or regional cropping practices, and of the deterioration of the natural vegetation under increasing population pressure, but have simply summarized what seemed important to our main theme.

Though this account is confined within fairly narrow limits and is addressed primarily to other soil men, we hope that it will not be too technical for the many with a smattering of soil science who are interested in the subject. We also hope it will be useful background reading for those specialists in other fields whose contributions are needed to fill in the story and set us new problems; and for the many who labour in the tropics to feed more and more people from land that is becoming less and less fertile.

It is a pleasure to be able to record here our thanks to Professor J. F. V. Phillips for his consistent support, to Mr. F. Bray for much useful discussion, and to F.A.O. for access to unpublished material.

Legon, June 1959

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# INTRODUCTION

## (a) An Outline of Shifting Cultivation

One of the most remarkable features of shifting cultivation is its universality. Primitive people evolving from the status of simple food gatherers, in which they had little more influence on the soil or vegetation than wild animals, have responded to the challenge of the forest in the same way. In regions so widely separated as the tropics of Africa, America, Oceania and south-east Asia they cut and burned the forest, planted their crops with a simple digging stick, and after taking one or two harvests they abandoned their plot to the invading forest. Each year a new patch of land was cleared, and hence the term—shifting cultivation. Later some of them developed the hoe, and with this implement they were able to clear tenacious grass roots and cultivate the savannas, abandoning their plots as in the forest after a few years of cropping. These regions, if not deserted, had hitherto been the domain of hunters and pastoralists, but with increasing population over-cropping gnawed at the fringes of the forest, and the savanna which replaced it became more and more important to agriculturists (Bartlett, 1956).

Shifting cultivation is practised on such a wide range of soils, amid so many types of vegetation, and by peoples of such widely varying origin and culture that it shows great variations in the types of crops grown, the length of the cropping and fallowing periods, and the methods of cultivation. To avoid over-generalizing on the one hand and excess of details and provisos on the other we shall describe some examples of shifting cultivation in the forest and savanna regions of West Africa in sufficient detail to bring out the main points needed to provide a working background.

West Africa is a particularly convenient region to consider because between the Gulf of Guinea and the Sahara Desert it contains broad east-west trending agricultural zones associated with an annual rainfall varying from over 200 in. to less than 10 in. Areas with a rainfall exceeding 50 in. p.a. and a dry season of less than four months are usually under closed forest, and this is divided into the moist semi-deciduous forest with rainfall under about 75 in. p.a. and the moist evergreen forest with more. The drier areas are under savanna grassland. Some characteristics of farming by shifting cultivation are shown in Plates 1 to 10, and the main types of fallow in Plates 11 to 14.

*The Forest.* The first sight of native subsistence farming in the semi-deciduous forest region, e.g. in Ghana, presents an appearance of bewildering confusion to any one familiar only with the pattern

of well ordered fields under single crops characteristic of more advanced systems of farming. There are no clear boundaries, individual fields can scarcely be discerned, and while some patches of land are definitely under crops, and others are under a thick regrowth of forest, there is a middle group in which perennial crops survive amidst a regrowth of forest which is gradually choking them. Some patches of land carry only one kind of crop, yet others appear to carry a mixture of up to half-a-dozen kinds in a seemingly haphazard arrangement. (An extreme example of mixed cropping is provided by the Hanunoo of the Phillipines who plant on the average 40 to 50 different crops on a single cultivated patch in the first year of cropping; each crop includes on the average 2 to 3 specific varieties (Conklin, 1957)). A pattern emerges from this higgledy-piggledy confusion if one follows the history of a single plot of land over a number of years. The story begins with a piece of forest of about one acre which a farmer has been allotted by his tribal chief for clearing. During the dry season he cuts down the lianes and small trees with a cutlass and the middle-sized trees with an axe, leaving only a few trees with a diameter exceeding about 2 feet that furnish a light irregular shade. When the mass of vegetation is dry he burns it, and the ash is left on the surface. As soon as the rains break he plants maize with a digging stick into the rich layer of friable humic porous topsoil, which has been developed under the forest fallow. This is about 2 in. deep and consists on the immediate surface mainly of broken worm casts. He does not disturb the soil between the planting holes, since he weeds the young crop by slashing with a cutlass. During this period much of the surface of the soil lies bare to the tempestuous early rains, which shatter the crumbs and casts on the surface and may float away ash in the surface run-off. During the growth of the first crop, or shortly after it has been harvested, the farmer plants cassava (*Manihot utilissima*) and, as a rule, other long-growing starchy crops such as cocoyam, (*Colocasia antiquorum* or *Xanthosoma sagittifolium*) and plantain (*Musa* sp.). Small patches of land may be reserved for peppers, okras, spinach plants and other vegetable crops usually managed by the women. The crops grow well ahead of the weeds, and by the end of the rainy season the land is well covered with vegetation. During the next year the plantains and some of the cassava and cocoyam will be harvested, while the remainder are left to grow further into a third or fourth year to be harvested as needed, or abandoned to the regrowth of forest. Thus after the first year the land has always a cover of vegetation. The developing 'bush' springs from the stumps and large roots left after clearing the previous fallow, and from germination of seeds already lying in the soil or carried in from adjoining areas of forest. The dense mass of the developing secondary forest is soon dominated by light-loving species, among which *Musanga cecropioides* (the umbrella tree), *Trema guineense*, and *Macaranga barteri* are often prominent.

Regrowth is rapid and the secondary forest may well be 20 feet high after five years and 50 feet after ten. If it is allowed to continue growing for twenty years the early dominants are replaced by the variety of slower-growing species found in the mature forest. Eventually an old secondary forest scarcely distinguishable from the original is developed.

When a fresh clearing is made the boundaries of the new patch will not necessarily coincide with those of the old. It is possible that part of the original patch may be cleared again after five years, another part after 10 and another after 20. Because of this irregularity in clearing and the merging of the crop and fallow periods it is not easy to be definite about their lengths, but three years of cropping alternating with eight years of fallow often appears to maintain fertility.

The mature evergreen forest and its secondary forms appear to the untrained eye much like the semi-deciduous forest. In this wet zone, as for example in Liberia and Sierra Leone, upland rice replaces maize as the first cereal crop. It is often interplanted or followed by cassava. Rather longer periods of fallow are usually considered to be necessary than in the semi-deciduous forest and it is thought that $1\frac{1}{2}$–2 years of cropping should be followed by about 10 years of fallow.

*The Savanna.* The moist savanna which adjoins the forest consists of tall tussocky grasses, up to 12 ft. high when in flower, amid a widely varying density of scattered, fire-resisting trees, rarely over 50 ft. high. The grass is usually burned every year, and the surface of the soil lies nearly bare through much of the dry season.

When a patch of land is cleared most of the trees are cut and burned, though some valuable species may be preserved, and small stems left for training yam vines. The soil has to be more thoroughly disturbed than in forest to get rid of the roots of the grasses. In a typical cropping sequence the soil is scraped into mounds about 2 ft. high with a hand hoe, while it is still moist at the end of the rains. The climbing yam (*Dioscorea* sp.) is planted in the mound, and a variety of 'side crops' such as maize, squash and beans are added at the beginning of the rains. The following year the yam mounds are destroyed, and maize and sorghum planted on narrow ridges. These may well run up and down the slope leading to considerable soil wash. The next year groundnuts, interplanted thinly with millet, complete the cropping phase of the cycle. It will be noticed that in contrast to the forest the land is without cover during the dry season, and it is exposed to the early rains for at least four weeks before a fair cover is formed. The labour of weeding is also more arduous, particularly if the rhizomatous grass, 'lalang' (*Imperata cylindrica*), is present. When the plot is abandoned it is dominated by *Pennisetum* sp. and other annual herbs if it is clean, or by 'lalang' if it is not. In a year or two the tall perennial *Andropogon gayanus*

appears and when in about ten years this has supplanted the 'lalang' the farmer considers the land is fit to clear again. If it is not cleared the *Andropogon gayanus* is replaced by other tall members of the Andropogoneae, such as *Hyparrhenia rufa*, to form a fire-climax which is established within twenty years.

As the rainfall diminishes and the dry season lengthens, the high-grass savanna is replaced by tall bunch-grass savanna standing about three feet high at flowering. The growing period is too short for yams, and cereals such as sorghum, millet (*Pennisetum* sp.) and eleusine, legumes such as groundnuts and beans, cotton, and sweet potato are the main crops. They are usually grown on ridges. The limit of dry-land cultivation is reached in the short bunch-grass savanna where millet growing during three rainy months is the main crop.

In the cropping systems that have been outlined maintenance of soil fertility depends almost exclusively on the resting fallow. Inorganic fertilizers, until very recently, have not been used, and organic manures are only available where cattle are kept, and even in these areas little use has been made of them. In the forest and the high-grass savanna cattle are rare because of trypanosomiasis, spread by the tsetse fly; and the other animals, the sheep, goats, dogs and fowls, are little more than disease-ridden scavengers around the villages. In the tall and short bunch-grass savanna there are herds of cattle, sheep and goats, but it is rare for their dung to be conserved. Cattle are in the main kept by tribes who concentrate on herding, like the Fulani of Northern Nigeria. However, there are some tribes who live in scattered homesteads, rather than villages, and keep the land around the homestead permanently under cultivation with the aid of the dung from domestic animals and other household refuse. Outside this 'compound farm' fertility is maintained as usual by shifting cultivation. Recently agricultural extension workers have had considerable success in developing this primitive 'mixed-farming' system by persuading farmers to cultivate with a bullock drawn plough and make proper manure from their increased numbers of cattle. The fertility of the compound farm is thus maintained at the expense of a wide area of grazing land.

(b) The Range of Shifting Cultivation

Although shifting cultivation is often regarded as a primitive system of agriculture of tropical regions, its practice is not confined to the tropics, nor are the peoples who employ it necessarily primitive, even in technology, let alone culture. Familiar though they were with the plough, the methods of shifting cultivation were adopted from the Indians by the early English settlers in Virginia in the 17th century (Carrier, 1923) and were still used till the middle of the 19th century: they were found to be the best answer to conditions in which there was abundant forest difficult to clear for ploughing,

and in which there was no other system worked out for maintaining fertility. To this day the European tobacco farmers of Southern Rhodesia rely largely on a natural savanna fallow to restore the fertility of the sandveld after taking one or two crops.

Set against a time scale extending deep into the neolithic period when man (or woman) first planted crops, it is well to recall how recently areas of Europe that now have the most progressive agriculture, were farmed by the methods of shifting cultivation. Parain (1942) clearly describes the situation in the temperate zone of western Europe during the Middle Ages:

"The two-course system had spread widely in Gaul and Britain, in the wake of the Roman legions, and perhaps even before their arrival. But in the poorer parts of these two countries, and in all Germany, much more primitive systems of temporary cropping—on forest land, moorland, and especially on open grassland over which the forest had not spread—were normal in the fifth century, and had not been altogether got rid of at the close of the Middle Ages. Forest land was sometimes regularly cleared, sometimes occupied for a time only, after the wood had been burnt to fertilize it. Clearing began on the plains, in valleys, and on the great terraces of mountain slopes. But on steep slopes and in high places difficult of access, men were satisfied with the temporary cultivation of ground burnt over—as they still are in Corsica and in the forest of Ardenne. As a rule only one crop was taken off it, originally oats, only from the eighteenth century also rye." He continues by describing the temporary cultivation of grassland:

"Part of the land was tilled for a year or a few years; then it lay fallow for many, and was used for grazing . . . . In Scotland temporary cultivation of the outfield was linked with the continuous cultivation of the infield without any fallow." The parallel with the 'compound-farming' system of the primitive tribes described in the previous section is striking.

There is confusion in the use of the term 'shifting cultivation', much of which turns on the point whether it is only the fields of the cultivators, or their homes as well as their fields which shift.

In the most undeveloped form of shifting cultivation farmers move their settlements as well as the fields they cultivate at frequent intervals, and the UNESCO Commission on World Land-Use Survey (1952) would have us restrict the term to such practice. The more developed tropical communities which abound in Africa and Asia, and occur more rarely in America live in fixed villages and farm the surrounding lands on a somewhat erratic rotation, a practice which the UNESCO Commission calls Land Rotation. In fact the two practices merge: thus among forest tribes, the Boro of the Amazon basin shift their settlements every few years; the people of Sa'a in Melanesia move when buildings become dilapidated, the cultivated land too remote, or if death and other misfortunes seem

to dog the place (Forde, 1934); the Ashanti in Ghana live in towns or villages that have endured for generations or even centuries. Recognition of a clear division between nomadic, semi-permanent, or permanent cultivators is also blurred by changes of population within a settlement. A family or clan will frequently move to found a new village or to expand an existing one. Nevertheless, so far as the soil is concerned what matters in all these cases is that the fertility of the land is improved by the natural regrowth of vegetation that springs up when cultivation 'shifts' to a new patch, and it is this process, together with the accompanying decline in fertility when the land is cropped that is being studied. We therefore use the term 'shifting cultivation' to describe cultivation practices rather than patterns of settlement.

Shifting cultivation nearly always involves clearing by burning, and in grassland it may in this way be distinguished from ley farming. It is frequently called 'slash and burn' agriculture; though the term 'swidden' farming is now preferred by some anthropologists, after the old English dialect word swidden—a burned clearing, resurrected by Ekwall (1955). These terms do not emphasize the temporary nature of the cultivation, and for this reason we prefer to retain the term 'shifting cultivation'. The practice is also referred to by a number of local names, among which 'milpa' from Central America, 'chena' from Ceylon, and 'kaingin' from the Philippines are common in the literature. Questions of nomenclature are more thoroughly discussed by Conklin (1954).

No one has yet published a detailed general survey of the system of shifting cultivation. Forde (1934) mentions many examples of this system in his stimulating study of the relations between primitive economies and cultures, and their physical environment. Bartlett (1956) has presented a well documented study of fire in relation to primitive agriculture which he has supplemented with two volumes of a splendidly annotated bibliography (1955, 1957) and he has a further three volumes in preparation. Gourou (1953) has set the system against the general background of the tropics and has particularly emphasized the contrast between the thinly populated lands of shifting cultivation, with a mean population density of 17 per square mile, with the densely populated alluvial rice lands which, for example, in the Tonkin Delta of Indo-China support 9 million people at a density of 1400 per square mile. F.A.O. in collaboration with Kellogg and Pendleton (1948) have given a well-balanced account of the effects of shifting cultivation on the soil, and many of the points they make are discussed in later sections. Whittlesey (1937) has given a general descriptive account.

Of the three great continental regions of shifting cultivation in the tropics*, Africa is the largest, has the greatest variety of natural conditions and cultural patterns, and has provided us with by far

* We shall, following Koppen's classification, consider the tropics to include all lands with a mean temperature in the coolest month above 18°C. (64·4°F.)

the most data. Of its total tropical area of $5\frac{3}{4}$ million square miles, Shantz and Marbut (1923) estimate just over 2 million to be under forest. Most of the remainder is savanna or open woodland. The population is 104 million—a density of 18 per square mile (Gourou, 1953). A small proportion are pastoralists, but the great majority live on food grown by shifting cultivation, and some produce export crops such as cotton, tobacco and groundnuts by the same method.

Harroy (1949) and Worthington (1958) both discuss shifting cultivation against the wider background of the conservation and development of the natural resources of Africa, and Hailey (1957) deals with it in its social and administrative setting. In regional accounts Irvine (1934) describes native practice in what was British West Africa, Waldock et al. (1951) in Sierra Leone, Tothill in the Sudan (1948) and Uganda (1940), Tondeur (1956) in the Belgian Congo, and Trapnell and Clothier (1937) and Trapnell (1943) in Northern Rhodesia. Among the detailed accounts of single tribes which illustrate their amazingly varied responses to the different soils and vegetation in their area de Schlippe (1956) has described the Zande on the border of the Sudan and the Congo, Bergeroo-Campagne (1956) the N'Dranouas in the high-grass savanna of the Ivory Coast, and Richards (1939) the Bemba in Northern Rhodesia.

Compared with Africa, tropical America has received far less scientific study. It is 5 million square miles, and like Africa has a great central mass of equatorial forest with a westward extension—into the Central American States. The forest is flanked by large expanses of woodland savanna to the south and smaller areas to the north, but these are very sparsely peopled. The population of the whole region is about 65 million—a density of 13 per square mile (Gourou, 1953).

Cook (1921) has described the 'milpa' system of growing maize by shifting cultivation in the forests of Central America. This shifting cultivation has attracted considerable interest because it supported the advanced Maya civilization.

The tropics of Asia are unlike those of Africa and America in that their area of 3 million square miles supports 530 million people, a density of 180 per square mile, or more than 10 times that of the other tropical continents. Most of these people are concentrated on alluvial soils and their staple food is swamp rice. A further number in India and Pakistan have developed settled systems of dry-land agriculture. Alongside these densely populated areas are the upland expanses of forest farmed by the usual system of shifting cultivation and supporting only about 16 people per square mile. Much of this forest has a rainfall exceeding 80 in. per annum, as in Malaya, Indonesia, Borneo, New Guinea and the Philippines, and upland rice is the main crop. Dobby (1950) estimates that one third of the total area used for agriculture in south-east Asia is under shifting cultivation.

Savannas comparable with those of Africa and America exist in

Burma, Siam and Indo-China, but are very sparsely populated. The grasslands formed by over-cultivation of the forests are dominated by lalang (*Imperata cylindrica*) which is too difficult to clear for cropping.

Pelzer (1948) has written the best general account of shifting cultivation in south-east Asia, and Gourou (1940) has described the practice in Indo-China. Conklin (1957) has made a detailed and valuable study of the agricultural practices of the Hanunoo in the Philippines, and so, too, has Freeman (1955) of the Iban in Sarawak.

There has been little detailed work in Asia or America that has been useful to us in dealing with our main theme, since the work done has been in the main devoted to plantation crops and swamp rice. However, in spite of the fact that most of the work has been done in Africa the conclusions drawn should be widely applicable to the other tropical continents since they have parallel ranges of soil and vegetation.

### (c) The Receding Forest

We have seen that lands of shifting cultivation support a population of less than 20 per square mile, and in general it appears that the system is fairly stable at that level. One of the main reasons why there is so much concern about the system is that it is now being forced to carry a load it was not developed to bear, and the effects of its breakdown are everywhere to be seen in the rapid disappearance of forest and woodland in favour of grassland savanna. The stages of this transformation are well known. Increased pressure on the land leads farmers to shorten the fallow period, and sometimes to prolong the cropping period, so reducing the fertility of the soil and the vigour of the forest regrowth when the land is abandoned. Some grasses and other herbs will always invade an abandoned clearing, but in normal circumstances the developing forest species rapidly suppress them. When, however, the woody regrowth is slow the herbs form a good cover. This may be burnt during the following dry season, killing the fire-tender suckers and seedlings of the forest trees; and thus the forest gives way to a 'derived savanna' maintained by annual burning. This process is most active on the margins of the forest where the rainfall is not too high, the dry season is marked, and grasses can readily colonize from adjoining areas of savanna. The effect of burning in maintaining a savanna is illustrated in Plates 15 and 16.

There has been much controversy about the area of savanna that is man-made (Bartlett, 1956). Much, if not all, of the savanna would certainly return to forest or closed woodland if protected from fire, but there is some doubt whether fire ignited by natural causes such as lightning would not be sufficient to maintain at least part of the savanna especially on poorly drained soils unfavourable to tree growth. All are agreed, however, that the rate of

destruction of the forest has greatly increased in the past century or two, particularly under the influence of European contact.

As will be shown in later sections the replacement of the forest by savanna grassland leads to a permanent lowering of the fertility of the soil. This is an interesting contrast to parallel changes in temperate regions where prairie soils are usually richer in nutrients than adjacent forest soils. It is possible that tropical soils under elephant-grass (*Pennisetum purpureum*) savanna are as fertile as they were under forest. Their extent is small, though important in the region of Lake Victoria.

In south-east Asia the forest gives way to areas dominated in the main by lalang (*Imperata cylindrica* var. *major*), and such areas are useless for cultivation. In the Philippines which were once almost entirely forested, some 17% of the total area is now covered with lalang (Bedard, 1958). There are further extensive areas in Sumatra, Malaya and Indo-China. In Africa and America the corresponding grasses *Imperata cylindrica* var *africana* and *Imperata braziliensis* are not so aggressive, and though troublesome weeds in over-cultivated land are rapidly replaced by other savanna grasses if left.

(d) The Response of the Soil

Many of the processes at work during the rise in the fertility of a soil under a natural fallow and its subsequent fall during cropping are clear in broad outline. Since there are considerable differences between the behaviour of the soil under forest and under savanna each will be discussed in turn.

At the start of the fallow period in forest the bush grows rapidly, partly from new seedlings and partly from a well elaborated root system inherited from the previous fallow. Of the plant nutrients taken up from the whole rooting zone, part will be stored in the increasing volume of vegetation and part will be returned to the surface of the soil in the form of litter and rain-wash from the living leaves. With the intense biotic activity in the soil surface the litter decays rapidly, and for most practical purposes the nutrients in it may be regarded as being added directly to the soil surface. The leaching of these nutrients under the high rainfall is restricted by the cover of vegetation, which, it is supposed, reduces percolation and is active in reabsorbing them. Losses by sheet erosion are greatly reduced by the reduction of the kinetic energy of the raindrops by the cover and by the litter layer on the surface, and by the porous granular structure that develops in the mineral soil beneath it. The result is that nutrients are transferred from the subsoil and stored partly in the standing vegetation and partly in the topsoil. Eventually, in the mature forest, a nearly closed cycle of nutrients between soil and vegetation is set up.

At the same time that the nutrients are increasing in the top soil so also is its content of humus. The leaves and wood falling on the surface build up a layer of litter. This is only about half an inch

thick with patches of bare soil showing through, because it is rapidly decomposed by a variety of organisms—most important being termites, worms, bacteria and fungi. Most of the carbon in the litter is lost as carbon dioxide. Some, however, remains and becomes incorporated with the mineral soil as quite stable humus. Oxidation of soil humus does not of course cease while the soil is under fallow, but in the early stages of the fallow the rate of increase exceeds the rate of oxidation, and the humus will continue to increase until it reaches the equilibrium level attained under a virgin forest.

Parallel with these chemical changes occur beneficial physical changes. The fine surface roots of the trees mould the soil into soft porous granules or crumbs, worms deposit their casts on the surface, and large numbers of drainage channels are created by the constant passage to the surface of termites and other animals. The surface of the soil is thus maintained in an excellent state to permit rapid infiltration of water, and to resist erosion.

When the forest is cleared and the debris burned all the nutrient elements except nitrogen and sulphur are deposited on the surface as ash and are washed into the soil by the first rain. Nitrogen, sulphur and carbon in the burned material are lost as gases. Much of the litter layer also is destroyed by the burning; consequently, the soil surface is bared to the sun and rain. Some of the ash may even be floated or blown off the site. The part of the litter not consumed in the burning is rapidly decomposed, and the rate of decomposition of the stable humus is thought to increase as a result of insolation, and the increased aeration associated with any cultivation of the surface soil. The amount of rainfall intercepted or transpired by the vegetation is now less, so that more is available for leaching; accordingly, loss of nutrient elements is thought to be rapid.

The physical condition of the surface deteriorates rapidly under the impact of the early rains and sheet or rill erosion may occur. These processes continue to a diminishing extent as the first crops cover the ground, though to the loss of nutrients by leaching is now added the loss to the growing crops. When the first crop has been harvested the soil surface may again be exposed to some extent, but intercrops, weeds and the trash of the harvest afford some protection. If, as in most parts of Africa, permanent crops have been planted there is usually a good cover by the end of the first year and the decline in fertility by oxidation, leaching and erosion is much reduced. In many parts of Asia, however, the land is again cleared the next year for a second crop of rice, and the processes of deterioration are repeated.

In the savanna the story is rather different. When the land is abandoned, and also after the burning that takes place each dry season, the grass and other herbs may be slow to form a complete cover over the ground. Every year until this is formed, the soil is exposed to the intense heat of the sun, and the early rains beat

upon its incompletely protected surface. Unlike the forest fallow the grasses do not continue to increase their store of nutrients year by year, and the growth of the scattered trees is slow, being retarded by fire. The burning also reduces the build-up of humus in the top soil by reducing the amount of litter supplied to the soil organisms.

The improvement in the physical condition of the top soil is also less marked than in forest. Owing to the absence of a complete soil cover, and the reduced amount of litter, the soil surface is more compact and less permeable.

When the savanna is burned and cleared for cropping far fewer nutrients will be deposited on the surface than in the forest. The thorough cultivation of the soil that is necessary to clear the tussocks of coarse grasses thoroughly aerates the soil, and is thought to accelerate the decomposition of the humus. The processes of leaching, erosion and crop removal already described for the forest now set in. A cover is established more slowly than in the forest, though the effect of this on leaching and erosion may be offset by a lower rainfall. However, at the end of the rains when the crops are harvested the surface of the soil is again left bare, and the destructive processes are thus repeated for each season of cropping.

While this broad picture is fairly well understood it is entirely qualitative and it leaves a host of important questions unanswered; for example, there was until recently remarkably little quantitative information about such basic aspects of the fallow period as the relative nutrient content of the soil and the fallow growing on it, the rate of the nutrient "cycle", or the rate of increase of humus and nutrients in the top soil. Similarly, for the cropping period it is only recently that quantitative experiments have revealed the amounts of nutrients that are added to the soil on clearing, and how fast they are lost by leaching, by erosion of top soil or by removal in crops.

In addition to analysing the effects of shifting cultivation on the soil, we have also to consider how far the nature and response of the soil accounts for the pattern of farming in the different regions. Here we are helped by recent work of agriculturists and anthropologists giving precise details of native practices.

In the following chapters the processes which have been briefly outlined are examined in greater detail, in the light of the quantitative information that has been obtained in the past fifteen years.

Part I deals with the processes of the fallow period. To provide a framework, we first describe and classify the important fallows and soils of the tropics. We then compare the amounts of nutrients stored in the fallows and in the soils. Next we consider the rate at which this store of nutrients is cycling from the soil to the fallow and back to the soil. Finally this and other processes are related to the increase in the fertility of the top soil that occurs under the fallow. Part II deals with the cropping phase, and includes first an account

of the effects of clearing and burning the fallow on the physical, chemical and biological properties of the soil. We then discuss all the factors associated with the decline in fertility of the soil during the progress of the cropping period. Part III deals with the system as a whole. It contains a discussion of its effects on the pattern of soil fertility in different regions, and an assessment of its merits as a method of tropical subsistence agriculture in the past and in the future.

# PART I—THE FALLOW PERIOD

## Chapter 1

## THE RANGE OF FALLOWS AND SOILS

### (a) The Types of Fallows

In arranging data on fallows and soils, and in investigating their influences on one another we think it essential to adopt an ecological approach, albeit often a tentative one. Study of the vegetation-soil ecosystem, as Tansley (1935) has called it, is complicated by very great modification, by human interference and climatic change, of the vegetation under which the soils were formed. Some important characteristics of a soil, such as its texture or the shape of the slopes on which it is developed, respond only slowly to changes in vegetation, while others such as the humus content of its surface horizon respond quite rapidly. In considering the properties of the soil one has therefore always to be thinking of what the vegetation and climate have been as well as what they are.

Accordingly, we shall examine the interrelations of fallows and soils in the tropics under the headings of the broad physiognomic types of their vegetation, and the scheme outlined in Table 1 will form the framework for the presentation and discussion of data. The secondary formations indicated opposite each climax formation, *pace* Richards (1958), are widespread in that zone, but are not necessarily restricted to it. The rainfall limits for each zone overlap, for the boundaries of the formations are affected by the distribution of the rainfall, temperature, etc., and the nature of the soil, as well as by the amount of rainfall.

Since there is no generally accepted terminology to cover the whole of the tropics, and most of our data come from Africa we have used so far as possible the provisional scheme of nomenclature recommended for Africa by a meeting of Specialists in Phytogeography held at Yangambi in 1956 (Boughey, 1957). A vegetation map of Africa using this nomenclature has recently been issued (A.E.T.F.A.T., 1959). Parallel climax formations occur in other parts of the tropics. A comparative account of forest formations has been made by Richards (1952). For the grasses we have used Bews's (1929) nomenclature. The main omissions in Table 1 are the vegetation of high altitudes, of desert and semi-desert zones, and of low-lying or swampy areas. In none of these types are fallows so important in maintaining fertility.

## TABLE 1

**Arrangement of Vegetation Climax and Secondary Formations with Special Reference to Africa**

| Rainfall in. p.a. | Climatic Climax Formations | Secondary Formations | |
|---|---|---|---|
| | | Mainly Woody | Mainly Grass |
| Over 65 | Moist evergreen forest | Secondary bush, secondary forest | *Imperata cylindrica* var. *major* grassland (Asian form) |
| 45–90 | Moist semi-deciduous forest | Secondary bush, secondary forest, semi-deciduous thicket | High grass savanna—*Imperata cylindrica* var. *africana* (African form) *Pennisetum purpureum* *Andropogon* spp. *Hypharrhenia* spp. |
| 35–65 | Dry deciduous forest | Deciduous thicket, Woodland | Tall bunch-grass savanna |
| Under 40 | Deciduous thicket | | Short bunch-grass savanna |

1. *The Climax Formations*

It is worth noting at the outset that all climatic-climax formations in the lowland tropics on free-draining soil are predominantly woody. The vast regions of savanna that occur in Africa, and to a lesser extent in Asia and America, are fire climaxes which originate from man's activity, or less often they are edaphic climaxes.

The Moist Evergreen Forest contains in a single locality a great variety of species of trees, shrubs and lianes, each in a range of sizes according to age and micro-habitat. In this way it differs greatly from many temperate forests. Because of the dense shade, the herb and under-shrub layer is sufficiently clear that one can walk through it without great difficulty. Typically, the lowest tree layer forms a fairly continuous canopy about 30 ft. high. Above this the canopies of taller trees may range up to 150 ft., often approximately segregating as a lower canopy in the zone 50–100 ft. with an upper canopy of the largest emergents appearing scattered as a discontinuous layer well above it.

In Africa the moist evergreen forest dominates the Central Congo Basin and parts of French Equatorial Africa, and forms outliers along the wettest parts of the west coast of Africa, in Nigeria, Liberia and Sierra Leone. In tropical America the analogue of the moist evergreen forest is the lower montane rain forest and the evergreen seasonal forest described by Beard (1944, 1946) as occurring in Trinidad in areas with a rainfall exceeding 72 in. p.a. These types of forest are also widely distributed in the Amazon Basin and the Central American States. In tropical Asia the expanse of evergreen rain forest has Singapore at its heart and extends over the Malay peninsula into Burma and India to the west, and to Sumatra, Borneo and New Guinea to the east.

The Moist Semi-Deciduous Forest, like the moist evergreen forest, is an immense closed high forest, but differs in containing a much higher proportion of deciduous species. These do not remain leafless for more than a month or two, and at no time are all the trees without leaves. Its boundary with the moist evergreen forest is ill defined.

In Africa the moist semi-deciduous forest surrounds the equatorial blocks of moist evergreen forest in Central Africa, and lies to the North of them in West Africa. In America the analogue of the moist semi-deciduous forest is that which Beard (1944, 1946) calls the semi-evergreen seasonal forest, occurring in Trinidad under a rainfall of 52–72 in. p.a. Similar formations adjoin the evergreen forest in the Amazon basin and Central America. In Asia, the Tropical Moist Deciduous Forest of Burma and India, described by Champion (1936) and developed under a rainfall of 60–90 in., appears to be the analogous formation, and a similar formation probably extends into Siam and Indo-China.

Dry Deciduous Forest is of lower stature. It is characterized by emergent species rising to 80 ft. that are leafless during much of the

dry season, and a dense understorey of deciduous woody species. Grasses are absent or rare in the herb layer. This formation, which may once have covered a vast area, is now very restricted in Africa and has mainly given way to 'derived savanna' and woodland. The Deciduous Seasonal Forest of Trinidad (Beard) and the Tropical Dry Deciduous Forest of Burma (Champion) are probably the analogous formations in America and Asia, respectively.

Deciduous Thicket includes a wide range of close-growing, often densely coppicing shrubs with grass absent or sparse in the herb layer. Scattered emergents may rise above the general level of the thicket, the striking Baobab tree (*Adansonia digitata*) being a common example in Africa. Under less than about 25 in. p.a. of rain the thicket is usually composed of Acacias or other thorny shrubs. Similar thickets occur in the American and Asian tropics.

2. *Secondary Formations*

When cultivated land is abandoned its vegetation as a rule passes through several secondary successions, but rarely reaches the climatic climax before the land is again cleared. The length of a fallow period depends to a great extent on the vigour of this secondary growth and its ability to eliminate undesirable species, usually grasses. We cannot here make a complete survey of the complex ecological problems associated with this succession, though we shall consider later those aspects that have a special bearing on the restoration of the fertility of the soil.

(i) *Woody formations*

Richards (1952) has made a fine survey of the secondary successions in the moist evergreen forest. He concludes:

"The first phase of the succession is dominated by weeds, including grasses, which are usually short-lived and are ephemerals rather than annuals since their life-cycle is often much shorter than a year. The next phase may be dominated by shrubs, but dominance often passes almost directly from herbaceous plants to trees . . . . Young secondary forest tends to be even-aged and is often dominated by a single species; the first dominants may form a single-generation community which dies without reproducing itself and is followed by communities with other dominants. In time the secondary forest becomes more mixed in age-structure and floristic composition till it approximates to the condition of mature forest."

In Nigeria and much of the Congo Basin, for example, the secondary succession is often dominated by the Umbrella Tree (*Musanga cecropioides*). This is a rapid-growing light-loving species with a high potassium content that dies out after about twenty years and is unable to regenerate in its own shade.

Further detailed study of the early stages of the succession has been made at Yangambi (Bernard et al., 1949) and in S.-W. Ghana (Ahn, 1959).

In the moist semi-deciduous-forest zone there is a greater variety in the floristic composition of the dominants in the succession and the secondary bush often appears as a "chaotic wilderness of trees, shrubs, herbs and climbers". The details of the succession depend very much on the degree of exhaustion of the land and the type of soil. Clayton's (1958) study of the succession in the farmland around Ibadan in Western Nigeria, give a good idea of the wide range to be encountered over a relatively small area.

In the dry deciduous-forest zone the secondary vegetation may take the form of a dense semi-deciduous thicket. A good example is the Guinea Coastal Semi-Deciduous Thicket found to the south of the high forest along parts of the west coast with rainfall of only 30 to 45 in. This consists of a mass of coppice shoots rising to a height of 25 ft. Frequent cutting for cropping encourages those woody species which coppice freely. The thicket is never leafless and the herb layer is absent.

Woodland is another deflected climax in the dry deciduous-forest zone. It consists of small or medium-sized trees forming a closed canopy which maintains only a thin leaf cover during much of the dry season. The understorey is open and the herb layer contains short grasses, frequently burned. In Africa woodland is widespread in the southern half of the continent, where it is known as 'miombo', and consists mainly of *Brachystegia* and *Isoberlinia* spp. In the northern half it occurs in a pure form only in small areas, its place being mainly taken by savanna. It is this woodland which gives rise to the 'chitemene' systems of shifting cultivation found in Northern Rhodesia, in which branches are lopped over a wide area and piled and burnt on a much smaller 'garden'.

(ii) *Savanna formations*

The savannas* consist of mixed formations of grasses and fire-resistant shrubs and trees up to 50 ft. tall. It is usual for the grasses to be fired every year. The density of the woody growth varies greatly according to the intensity of cultivation, the method of clearing, and the severity of the annual burn: in Grass Savanna, trees and shrubs are absent or very isolated, while in Tree Savanna the numerous protected trees give an impression of parkland; still more densely wooded grassland is known as Savanna Woodland.

Some account must be given here of the different grasses, for we shall be concerned in later sections with their succession on abandoned land; and with their productivity and floristic composition,

* Beard (1953) defines 'savanna' as a physiognomic unit of vegetation as follows:

"Savannas are communities in tropical America comprising a virtually continuous, ecologically dominant stratum of more or less xeromorphic herbaceous plants, of which grasses and sedges are the principal components and with scattered shrubs, trees and palms sometimes present."

By laying emphasis on the herb layer as the ecologically dominant stratum this definition satisfactorily separates savanna from woodland and forest.

which influence the amount and ease of mineralization of the humus built up beneath them.

The classification we use is that of Bews (1929), and is based on the height and hygrophilous character of the grasses. Though depending largely on African experience, Beard (1953) has found it satisfactory for American savanna.

The high-grass savanna is dominated by very tall coarse grasses from 5 to 15 feet high at flowering. The species are members of two tribes, the Paniceae containing notably *Pennisetum purpureum* (elephant grass) and *Panicum maximum* (Guinea grass), and the Andropogoneae containing notably *Imperata cylindrica*, (not always a 'high' grass, often being under 5 ft.), *Andropogon gayanus*, and *Hyparrhenia* spp. The high-grass savanna forms the fire climax in regions where the rainfall exceeds about 45 in. p.a. and the dry season lasts up to 6 months.

In Africa much of the land now under high-grass savanna was once under moist semi-deciduous or, rarely, moist evergreen forest. The Paniceae tend to be dominant in moister areas with short dry season; for example elephant grass, the tallest and most productive of African grasses, is extensively developed in southern Uganda. It also occurs in parts of West Africa immediately to the north of the present forest boundary. The Andropogoneae dominate a much larger area, adjacent to the high forest. In the northern hemisphere they stretch across the continent from the Atlantic Coast of Guinea in the west to the upper reaches of the White Nile in the east; and in the southern hemisphere they dominate the southern half of the Belgian Congo.

An excellent account of the savannas of tropical America has been given by Beard (1953). Here, man aided by fire has caused far less destruction of the primaeval vegetation than in Africa, and the degraded forest type of habitat is less common. True high-grass savanna, according to Beard, has not yet been recognized, though *Imperata braziliensis*, the American analogue of *Imperata cylindrica*, does occur in overcropped land. In Asia, large areas of the Phillipines and Indonesia, and smaller areas in other parts of the former moist-forest region have been replaced by 'cogonales'. The dominant grass is *Imperata cylindrica* var. *major*, and *Saccharum spontaneum* is frequently mentioned. Unlike the African variety of *Imperata cylindrica*, which is displaced in a few years by other grasses easier to clear for cultivation, the Asian form is the fire climax, and these cogonales are useless to the cultivator. If protected from fire they will eventually return to forest.

The grasses of the tall-bunch-grass savannas are about 3 ft. high at flowering, and are dominated in the climax stage by the Andropogoneae. Trees and shrubs vary greatly in density according to the intensity of cultivation, burning and grazing, and the type of soil, ranging from almost total absence to a closed canopy of woodland. In Africa, the tall-bunch-grass savanna of the northern

hemisphere lies between the high-grass savanna and the short bunch grasses and semi-desert grasses and scrub on the fringe of the Sahara. In the southern hemisphere it covers much of the Rhodesias, and dominates East Africa from Zululand to Zanzibar. It grades into the short-bunch-grass savanna at a rainfall of about 35 in.

In America, tall-bunch-grass savanna, entirely analogous to the African form, is widespread, notably on the Brazilian plateau, the Guiana highlands, and the Orinoco plains.

The short-bunch-grass savannas are about 1 foot high at flowering. The short grasses and scattered flat-topped Acacia trees are a familiar sight in the northern and southern hemispheres of Africa under rainfalls of 20 35 in. Much of this region is too dry for successful rain-land cultivation. In tropical America and Asia short-bunch-grass savanna is very restricted since areas with rainfall under 35 in. p.a. are limited.

### (b) The Types of Soils

The existing general accounts of the soils of the tropics, for example by Mohr and van Baren (1954), are not concerned with the soil as a medium for growing crops, and scarcely mention the characteristics of the soils and their relation to the fallow vegetation that primarily concern us. The brief survey of some tropical soils that follows only attempts to bring out those features which are of significance for the purpose of this account. It is restricted largely to the free-draining mature soils of the uplands because they are the only ones on which the relation between soil and fallow has been studied. They have been variously termed tropical red earths, lateritic earths, ferrallitic soils and latosols. These highly weathered soils are developed on a vast scale over the great ancient continental land masses of the tropics. On them, the nutrients in the soil and the growing fallow form a closed cycle with only a slow leak to drainage. We shall have much less to say about younger soils whose nutrient supplies are maintained by decomposition of unweathered minerals, as, for example, in soils developed from volcanic ash or in shallow soils on steep slopes; or about those rejuvenated by fertile silt deposited by floods, as, for example, the alluvial rice lands of Asia. On all these soils continuous cropping is often possible. We make no specific mention either of highland soils (above 4,000 ft.). The general principles in the following account apply to them with the exception that their organic-matter levels tend to be higher, and the rainfall limits within which any group appears, are reduced corresponding to the lower evaporation.

In the absence of any generally recognized system of classifying tropical soils below the level of sub-order in the U.S. scheme (e.g. latosol), we have adopted the relevant parts of the scheme of classification proposed by C. F. Charter (Brammer, 1956). These are shown below.

| *Order* | *Sub-Order* | *Great Soil Group Family* | *Great Soil Group* |
|---|---|---|---|
| Climatophytic Earths | Hygroped | Latosol | Forest Oxysol<br>Savanna Oxysol<br>Forest Ochrosol<br>Savanna Ochrosol |
| | | Basisol | Forest Rubrisol<br>Savanna Rubrisol<br>Forest Brunosol<br>Savanna Brunosol |
| | Xeroped | | |
| Topoclimatic Earths | Planoped | Calcium planosol | Tropical Black Earth<br>Tropical Brown Earth |

This scheme comes nearer to satisfying our purpose than any other, for it is squarely based on genetic factors, and encourages thinking about soil-forming processes. All the soils mentioned, with the exception of the tropical black and brown earths, would be classified as latosols on the U.S. system.

1. *Latosols*

Latosols are the zonal or climatophytic soils of the tropics. They are characterized by reddish hues and stable micro-aggregation which promotes free drainage. The clay fraction is composed mainly of kaolinitic minerals with iron and aluminium oxides. The great majority of latosols are developed over quartzose rocks: prominent among them are the granites and gneisses of the basement complex, acidic schists and phyllites, sandstones, shales and unconsolidated deposits. They are also formed over basic rocks, though these frequently give rise to basisols, described later. Among latosols, a division is made between the soils showing the characteristics of excessive leaching called Oxysols (oxus = sharp), and those less thoroughly leached, called Ochrosols (eu chros = well coloured). This division is of great significance in any discussion of the fertility of tropical forest soils, but it has been little appreciated in published accounts. The distinction between the two groups was first clearly made by Vine (1953*a*) for Nigerian forest soils. A further important distinction is made between soils under forest and under savanna.

(i) *Forest oxysols*

In regions of high rainfall corresponding approximately to the moist evergreen-forest zone the rocks are in general weathered to depths of 20 ft. and more, and there are few undecomposed minerals,

except the most resistant ones, within reach of plant roots. The predominantly quartzose rocks and the intense eluviation of clay give rise to marked textural profiles with light open top soils and heavier more compact subsoils. The organic matter is concentrated markedly in the top few inches. It makes the largest contribution to the exchange capacity of the surface horizons, and is therefore largely responsible for holding their nutrient cations. In the subsurface horizons the exchange capacity is low, due to the predominance of kaolinitic clay minerals and the high proportion of sesquioxides.

The following characteristics differentiate the forest oxysols from the forest ochrosols which form the next group to be described. The pH is 4·0–4·5 in the topsoil, gradually increasing to 4·5–5·0 in the subsoil. The C/N ratio tends to be high, over 15. The colour of the mineral soil is usually brown or orange brown rather than red or reddish brown. If the forest vegetation is cut and burnt profound changes in the microbiological population occur (Dommergues, 1954a and b).

Soils with these characteristics have been described from most of the moist evergreen-forest regions of the world. In Africa they predominate in Liberia (Reed, 1951), Sierra Leone (Martin and Doyne, 1932), in parts of Ghana with over 70–80 in. annual rainfall (Brammer, 1960), in parts of Nigeria with over 80 in. annual rainfall (Vine, 1956), in the central Congo Basin (Kellogg and Davol, 1949), and in Madagascar (Pernet, 1954). In America they have been described in British Honduras (Charter, 1940), and Puerto Rico (Roberts, 1942). In Asia they are described in Malaya (Owen, 1951), and in Indonesia (van der Voort, 1950).

(ii) *Forest ochrosols*

In the rainfall areas corresponding approximately to the moist semi-deciduous forest the characteristics of the soils developed under a wetter climate are modified in the following important respects:

The topsoil is neutral or slightly acid and becomes increasingly acid at depth. Typical reactions are pH 6·0–7·0 in the upper topsoil, some 2 in. deep, and pH 5·5–6·5 in the lower topsoil, falling rapidly to pH 4·5–5·0 in the subsoil. The surface horizons thus hold many more nutrient cations. The mineral-soil colours tend to be red or reddish brown. The C/N ratio of the humus is 10–12, and the microbiological population is relatively stable.

There is no sharp boundary between the oxysols and ochrosols and intergrades are common. Oxysols are regularly developed, except over basic rocks, when the rainfall exceeds 80 in. p.a. and ochrosols when it falls below 60 in.

The ochrosols have been well described in Ghana (Brammer, 1960), Nigeria (Vine, 1956), the Lower Congo where they are described as Red Latosols under forest (Kellogg and Davol, 1949),

and Uganda (Tothill, 1940). They have been described also in Trinidad (Hardy et al., 1936), and Puerto Rico (Roberts, 1942).

In savanna regions there is also a division between savanna oxysols and savanna ochrosols. Oxysols bearing savanna have been described by Berlier *et al.* (1956) in the Ivory Coast, and they also occur, for example, in Sierra Leone and south-eastern Nigeria under rainfalls exceeding 80 in. p.a.

(iii) *Savanna ochrosols*

Soils under high-grass savanna are generally shallower than under forest, and rotting rock is often found within ten feet of the surface. However, over vast stretches of savanna the rooting zone is often restricted by the presence of indurated iron-oxide-cemented pan, often referred to as laterite, above the rotting rock. The organic-matter content of the surface horizons is considerably less than in forest soils, because of the reduced additions of organic matter from the vegetation, and consequently the exchange capacity is lower. The pH of the topsoil is slightly acid to acid and falls slowly, if at all, with depth. The content of exchangeable cations and of total and available phosphorus is lower than in the semi-deciduous forest zone. Many of the soils now under high-grass savanna may have been until fairly recently under forest, and some caution is needed in associating them too closely with this vegetation.

Under the low rainfall of tall-bunch-grass savanna regions the soil is shallower, the textural profile is less developed, and the content of organic matter is lower. The upland soils usually remain hygropeds, for the rainfall in one or two months of the year is usually sufficiently heavy for leaching to occur throughout the profile. Xeropeds in which the profile is incompletely leached, with accumulation of cations in the subsoil, do, however, occur. Accounts of savanna soils supported by analytical data have been given for Ghana (Brammer, 1960), Nigeria (Vine, 1956), Northern Rhodesia (Ballantyne, 1958), Southern Rhodesia (Ellis, 1951) and Madagascar (Pernet, 1954).

The fact that the clay minerals over this great range of latosols consist mainly of kaolin and sesquioxides introduces a remarkable uniformity in their chemistry. Because of the low exchange capacity of the clay fraction the content of cations is closely related to the pH and amount of organic matter. There is thus a general trend in nutrient content, particularly evident in the case of Ca and Mg, from very low in the forest-oxysol regions of very high rainfall and low pH, rising to a maximum in the forest ochrosols of relatively high pH and organic matter under the semi-deciduous forest, and falling steadily in the savanna with decreasing rainfall and organic-matter content. Typical analytical data for the soils are given in Table 3.

2. *Basisols*

In the moist evergreen-forest zone leaching is usually sufficiently intense for soils with the defining characteristics of the oxysols to develop even from basic rocks. Under the moist semi-deciduous forest the high Ca and Mg content of the rocks tends to promote formation of illitic and montmorillonitic as well as kaolinitic clays. This leads to soils that are more plastic and sticky, with more developed blocky or prismatic structure, and higher exchange capacity than the typical ochrosols. Charter called these soils Forest Rubrisols when they were dark red and Forest Brunosols when they were dark brown in colour. Because they are developed from non-quartzose rocks these soils are clays and lack a pronounced textural profile.

The basisols are far less extensive than the latosols in the tropics as a whole, though very important where they occur.

In the savanna, with reduced leaching, the tendency to the development of montmorillonitic and illitic clays over basic rocks is more pronounced, and tropical black and brown earths of high exchange capacity well saturated with calcium are common. In soils such as these, fallows are much less important in maintaining fertility; for instance, the black cotton soils of India developed over basalt have been cropped without break for over 100 years. In Africa, the black clay soils have proved too difficult to work with a hand hoe and are seldom cropped by peasant farmers.

## Chapter 2

## THE AMOUNTS OF NUTRIENTS IN THE FALLOW AND SOIL

Having outlined the range of vegetation and soils found in areas under shifting cultivation we may now consider how much nutrient 'capital' is banked within the ecosystem, how it is distributed between the vegetation and the soil, and how rapidly it moves from the one to the other. In this chapter we deal with the amounts and distribution of nutrients—that is with the static aspects of the system. In the next chapter we deal with the uptake of nutrients by the fallow and their return in the litter—that is, with the dynamic aspects, or, as it is known, the 'nutrient cycle'.

In order to give a quantitative account of the nutrients in the ecosystem one needs to know:

1. The nutrient content of each of the soil horizons: both the total amount and amounts readily available to plants in the exchangeable pool.
2. The nutrient composition and weight of the litter on the soil surface.

## TABLE 2

### Nutrients Stored in Typical Tropical Fallows

| Example No. | Place | Rain (in. p.a.) | Fallow | Part | Oven-dry Wt. 1,000 lb./acre | Composition % | | | | | Nutrients Stored lb./acre | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | N | P | K | Ca | Mg | N | P | K | Ca | Mg |
| | | | | **Moist Evergreen Forest** | | | | | | | | | | | |
| 1 | Kade, Ghana | 65 | 40 year mature secondary forest | Trash | 22·7 | 1·88 | 0·126 | 0·76 | 1·90 | 0·26 | 428 | 29 | 173 | 433 | 59 |
| | | | | Lianes | 12·9 | 1·18 | 0·051 | 0·43 | 1·94 | 0·15 | 152 | 7 | 56 | 250 | 19 |
| | | | | Wood with bark | 154·5 | 0·42 | 0·026 | 0·24 | 0·58 | 0·09 | 652 | 40 | 378 | 897 | 149 |
| | | | | Dead wood | 64·1 | 0·32 | 0·026 | 0·05 | 0·73 | 0·07 | 205 | 17 | 32 | 468 | 46 |
| | | | | Stumps | 43·7 | 0·38 | 0·040 | 0·19 | 0·38 | 0·07 | 166 | 18 | 83 | 166 | 31 |
| | | | | Litter | 2·0 | 1·54 | 0·057 | 0·45 | 1·98 | 0·24 | 31 | 1 | 9 | 40 | 5 |
| | | | | Roots | 22·1 | 0·86 | 0·045 | 0·35 | 0·59 | 0·18 | 191 | 10 | 78 | 130 | 39 |
| | | | | Total (excluding roots) | 300 | | | | | | 1634 | 112 | 731 | 2254 | 309 |
| 2 | Yangambi, Belgian Congo | 73 | 18 year secondary forest | Leaves | 5·8 | 2·2 | 0·12 | 1·24 | 1·18 | | 130 | 6 | 72 | 69 | |
| | | | | Woody matter | 104 | 0·26 | 0·05 | 0·27 | 0·33 | | 270 | 56 | 274 | 340 | |
| | | | | Dead wood | 15 | | | | | | 32 | 1 | 8 | 32 | |
| | | | | Litter | 5·0 | 1·36 | 0·05 | 0·145 | 1·20 | | 67 | 2 | 7 | 60 | |
| | | | | Roots | 28 | 0·47 | 0·11 | 0·64 | 0·85 | | 126 | 31 | 170 | 230 | |
| | | | | Total (excluding roots) | 130 | | | | | | 499 | 65 | 361 | 501 | |
| 3 | Yangambi, Belgian Congo | 73 | 5 year secondary forest | Leaves | 5·1 | 2·2 | 0·12 | 1·41 | 1·38 | | 112 | 6 | 71 | 70 | |
| | | | | Woody matter | 64 | 0·26 | 0·02 | 0·34 | 0·20 | | 162 | 12 | 218 | 123 | |
| | | | | Dead wood | 2·2 | | | | | | 4 | | 5 | 5 | |
| | | | | Litter | 6·6 | 1·08 | 0·04 | 0·21 | 0·96 | | 71 | 3 | 13 | 63 | |
| | | | | Roots | 23 | 0·69 | 0·03 | 0·44 | 0·50 | | 160 | 7 | 101 | 115 | |
| | | | | Total (excluding roots) | 78 | | | | | | 349 | 21 | 307 | 261 | |
| | | | | **Moist Semi-Deciduous Forest** | | | | | | | | | | | |
| 4 | Congo | 50 | High Forest | Wood | 242 | 0·266 | 0·023 | 0·200 | 0·302 | 0·075 | 644 | 55 | 484 | 730 | 181 |
| | | | | Bark | 30 | n.d. | 0·083 | 0·615 | 2·29 | 0·151 | | 25 | 185 | 687 | 45 |
| | | | | Trash } from | (22) | | | | | | (428) | (29) | (173) | (433) | (59) |
| | | | | Litter } Ex. 1 | (2) | | | | | | (31) | (1) | (9) | (40) | (5) |
| | | | | Total | 296 | | | | | | 1103 | 110 | 851 | 1890 | 290 |
| 5 | Kumasi, Ghana | 60 | 20 year (approx.) secondary forest mean values for 14 semi-decid. spp. | Leaves | (5) | 2·52 | 0·136 | 0·85 | 1·54 | 0·48 | (126) | (7) | (43) | (77) | (24) |
| | | | | Stem | (100) | 0·32 | 0·025 | 0·30 | 0·31 | 0·15 | (320) | (25) | (300) | (310) | (150) |
| | | | | Litter | (5) | 1·29 | 0·054 | 0·44 | 1·59 | 0·31 | (65) | (3) | (22) | (80) | (16) |
| | | | | Total | (110) | | | | | | (511) | (35) | (365) | (467) | (190) |
| 6 | Benin, S. Nigeria | 72 | 6 year fallow *Acioa barteri* | Leaves and twigs | 4·7 | 1·24 | 0·10 | 0·67 | 0·70 | 0·44 | 58 | 5 | 31 | 33 | 21 |
| | | | | Stem | 24·2 | 0·34 | 0·04 | 0·37 | 0·27 | 0·22 | 82 | 10 | 89 | 65 | 53 |
| | | | | Litter | 12·7 | 1·08 | 0·07 | 0·28 | 0·84 | 0·45 | 137 | 9 | 35 | 107 | 57 |
| | | | | Roots | (9·4) | 1·1 | 0·12 | 0·42 | 0·19 | 0·30 | (104) | (10) | (40) | (18) | (28) |
| | | | | Total (excluding roots) | 42 | | | | | | 277 | 24 | 155 | 205 | 131 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7 | Bambesa, Belgian Congo | c.70 | Elephant Grass 2 years old | Leaf and Litter Total | 36 | 1·8 | 0·05 | 1·1 | 0·25 | 0·35 | 292 | 20 | 400 | 89 | 126 |
| 8 | Europe | | Temperate hardwoods 100 years old | Leaves | (3) | | 0·258 | 0·81 | 2·29 | | | 7 | 29 | 57 | |
| | | | | Brush | (30) | | 0·053 | 0·20 | 0·62 | | | 15 | 60 | 183 | |
| | | | | Stemwood | (160) | | 0·011 | 0·069 | 0·115 | | | 17 | 107 | 227 | |
| | | | | Stembark | (19) | | 0·078 | 0·263 | 2·66 | | | 14 | 52 | 530 | |
| | | | | Roots | | | | | | | | (8) | (36) | (143) | |
| | | | Total (excluding roots) | | (212) | | | | | | | 53 | 248 | 997 | |
| | | | | | Dry Forest and Savanna | | | | | | | | | | |
| 9 | Southern Ghana | 35–40 | Coastal Thicket c.10 years old | Leaf | (2·6) | 2·12 | 0·140 | 1·41 | 1·46 | 0·43 | (55) | (4) | (37) | (38) | (11) |
| | | | | Woody matter | 45 | 0·35 | 0·040 | 0·39 | 0·64 | 0·16 | 157 | 18 | 175 | 288 | 72 |
| | | | | Litter | (4·1) | 0·96 | 0·079 | 0·87 | 1·67 | 0·24 | (39) | (3) | (36) | (68) | (10) |
| | | | Total | | 51·7 | | | | | | 251 | 25 | 248 | 394 | 93 |
| 10 | Copperbelt, N. Rhodesia | c.50 | Miombo Woodland | Woody matter | 90 | | 0·05 | 0·17 | 0·39 | 0·10 | | 45 | 153 | 351 | 90 |
| 11 | Ejura, Ghana | 59 | High-grass (Andropogoneae) savanna undisturbed over 20 years | *Herb Layer* | | | | | | | | | | | |
| | | | | Aerial parts | 6·8 | 0·29 | 0·087 | 0·54 | 0·42 | 0·29 | 20 | 6 | 37 | 29 | 20 |
| | | | | Litter | 1·1 | 0·34 | 0·077 | 0·39 | 0·20 | 0·26 | 4 | 1 | 4 | 2 | 3 |
| | | | | Roots 0–12 in. | 3·4 | 0·34 | 0·097 | 0·31 | 0·05 | 0·16 | 12 | 3 | 10 | 2 | 5 |
| | | | | *Trees* | | | | | | | | | | | |
| | | | | Leaf | (0·5) | 1·15 | 0·152 | 0·90 | 1·64 | 0·60 | (6) | (1) | (5) | (8) | (3) |
| | | | | Stem | (48) | 0·17 | 0·026 | 0·26 | 0·42 | 0·11 | (83) | (12) | (125) | (202) | (53) |
| | | | Total | Herb (no root) | 7·9 | | | | | | 24 | 7 | 41 | 31 | 23 |
| | | | | Trees | (48·5) | | | | | | (89) | (13) | (130) | (210) | (56) |
| 12 | Ejura, Ghana | 59 | *Imperata cylindrica* | Leaves, stems and litter | 3·5 | 0·43 | 0·140 | 0·88 | 0·17 | 0·34 | 15 | 5 | 31 | 6 | 12 |
| | | | | Roots and stolons | 7·9 | 0·33 | 0·156 | 0·80 | 0·08 | 0·11 | 26 | 12 | 63 | 6 | 9 |
| 13 | Marandellas, S. Rhodesia | 35 | Natural Grassland | Grasses | 1·3 | 0·65 | 0·11 | 1·2 | 0·29 | | 8 | 1 | 16 | 4 | |
| | | | | Other plants | 0·9 | 1·32 | 0·11 | 1·2 | 0·98 | | 12 | 1 | 11 | 9 | |
| | | | Total | | 2·2 | | | | | | 20 | 2 | 27 | 13 | |

Notes

Figures estimated or measured very approximately are given in brackets.

Example 1—Trash includes leaves and small wood up to 2 in. diameter.

Example 4—The volume of timber, 400–600 cu. m. per hectare, was obtained from measurements of all species with diameter greater than 20 cm. in a number of sample areas, e.g. see Lebrun 1934b. The error involved in neglecting species less than 20 cm. will be small, for their proportionate volume is low. The bark percentage 11% is based upon measurement of 16 trees (8 different spp.) in the semi-deciduous forest of Nigeria (MacGregor, 1934). 1 cu. ft. of tropical forest timber has been estimated to weigh 38 lb. oven-dry, based upon the average air-dry weight (12% moisture) of 48 Gold Coast timbers. (Forestry Dept. Gold Coast, 1949).

Example 6—Recent leaf fall accounts for the high litter.

Example 8—The contents of the elements in the different organs have been averaged from the original data listed by Rennie (1955). The total nutrients stored are those deduced by Rennie. The weight of the organs are approximate only.

Example 9—The weight of leaf and litter and the composition of the litter were measured on a fallow of similar composition, 4 years old. 10-year thicket yielded 14·9 cords per acre.

Example 10—Leaves and brushwood will make a small additional contribution. The herb and litter layer is thin in closed Miombo and storage should be slight, no greater than in example 11.

Example 11—The weight and composition of the grassland and the average composition of the trees and shrubs were determined directly. The weight of wood is based on the fact that savanna of this tree density with approximately quarter closed canopy yields about 16 cords of wood per acre. 1 cord contains c.75 cu. ft. wood, 1 cu. ft. is estimated to weigh 40 lb. oven-dry. At this density the trees do not appreciably reduce the growth of the tall grasses.

3. The nutrient composition and weight of all parts of the growing fallow including its roots.

These items can be measured directly, and the main problems are to make significant selections from the vast range of soils and fallows, and to sample the heterogeneous vegetation for determination of its weight and composition. This is particularly difficult in forest of mixed composition, for plots of several acres are required for a truly 'representative' sample of each of the various communities. Nevertheless although only approximate methods are often possible, differences between fallows, and between soils, are often so striking that they can readily be revealed by work on examples that can be described as 'fairly representative'.

A summary of available information on the composition of natural fallows is given in Table 2, and analytical data for the soils supporting the fallows are given under the corresponding number in Table 3*. For comparison with soils and fallows and for later discussion the amounts of nutrients removed in the harvest of some common native food crops are given in Table 4.

There are broadly two methods of arriving at the nutrients stored in forest-fallow vegetation, and examples of both of them are presented in Table 2. The direct method is to select an area of forest, cut it down, weigh or measure the amounts of leaves, brushwood, timber, etc., which are sampled for determination of their nutrient composition. The soil beneath the fallow is also sampled. If this formidable task is accurately carried out it yields true values for

* Ideally, the soil data should give (a) the total nutrients in each soil horizon, and (b) the pool of exchangeable nutrients taking part in the nutrient cycle, namely the exchangeable cations and also the exchangeable P. For the cations, in nearly every example only the values for the exchangeable forms are available. Data for exchangeable and total cations in a wide range of 12 forest soils in the Ivory Coast indicate that the ratio of total and exchangeable cations in topsoils (0–20 cm) is 2·2–10·4 for K, 1·2–3·7 for Ca, and 2·0–8·4 for Mg. In the Nigerian forest a similar range has been found (Tinker, priv. comm.). Results for K in 6 forest topsoils in Ghana show a similar range, but in 5 savanna topsoils, less weathered, the range was 20–120. For P the situation is less satisfactory. The pool of soil P involved in the nutrient cycle is represented by the 'exchangeable' phosphorus—best measured as the portion of the total phosphorus which will equilibrate with a solution containing the radioactive isotope $P^{32}$. It is nearly equivalent to the now widely used 'A value' or 'L value'. For African soils only values of 'available' P, usually extracted by the Truog method, have usually been recorded. Where both have been measured on the 0–6 in. layer of four latosols in Ghana, the 'L values' ranged from 1·3 times the Truog 'available' P, in a loamy sand of low phosphorus adsorption capacity, to 12·1 on a ferruginous clay of high adsorption capacity. This must be kept in mind when evaluating the data in Table 3. The total P exceeds the 'available' P by a factor of between 20 and 100 in the soils of Liberia, Ghana, and the Congo, and it will be seen that the amounts in the top 12 in. of soil greatly exceed the amounts stored in any of the fallows.

It must be remembered, especially for P and K, that there is a slow interchange between non-exchangeable and exchangeable forms and if the exchangeable form is severely depleted, for example by a period of cropping, the loss will be partially made good from the non-exchangeable forms.

## TABLE 3

### Nutrients Stored in Soils under Typical Fallows

| Corresponding fallow No. | Place | Top-soil Description (All free draining latosols except No. 14) | Depth in. | Composition pH | C % | N % | *Avail. P p.p.m. | Exch. (m.e./100 g) K | Ca | Mg | Total Nutrients (approx.) in 0–12-in. layer (lb. per acre) N | *Avail. P | Exchangeable K | Ca | Mg |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Oxysols of Moist Evergreen Forest** | | | | | | | | | | | | | |
| 1 | Kade, Ghana | Mid slope brown loam over phyllite | 0–2 | 5·3 | 2·28 | 0·198 | 8·4 | 0·46 | 5·52 | 1·11 | 4100 | 11 | 580 | 2300 | 330 |
| | | | 2–12 | 4·7 | 0·74 | 0·101 | 2·0 | 0·33 | 2·32 | 0·59 | | | | | |
| 1A | Liberia | Forest Latosols Mean of over 100 profiles over basement complex | 0–3 | 4·5 | 3·5 | 0·19 | 8 | 0·89 | 1·51 | 0·70 | (3600) | | | | |
| | | | 3–6 | 4·0 | 1·4 | 0·09 | 5 | 0·17 | 0·54 | 0·42 | | 23 | 410 | 464 | 203 |
| | | | 6–9 | 3·9 | | | 5 | 0·13 | 0·41 | 0·26 | | | | | |
| 2 & 3 | Yangambi, Belgian Congo | | | | | | | | | | 2000–3000 | 17 | 320 | 89 | 47 |
| | | **Ochrosols of Moist Semi-Deciduous Forest** | | | | | | | | | | | | | |
| 5 | Kumasi, Ghana | Upper slope dark brown coarse sandy loam over granite | 0 2 | 6·4 | 3 2 | 0 30 | 7 | 0·22 | 8·4 | 1·8 | 6000 | 13 | 220 | 4200 | 450 |
| | | | 2–6 | 6·4 | 1·3 | 0·12 | 3 | 0·15 | 5·5 | 1·0 | | | | | |
| | | | 6–12 | 6·2 | 0·9 | 0·09 | 2 | 0·10 | 3·9 | 0·6 | | | | | |
| 5A | Ghana | Latosols Mean of 51 Profiles over granites and schists | 0–2·7 | c.5·8 | 5·1 | 0·39 | 15 | 0·55 | 10·2 | | 7200 | 19 | 382 | 2720 | |
| | | | 2·7–8·3 | c.5·3 | 1·6 | 0·13 | 3 | 0·25 | 2·1 | | | | | | |
| | | | 8·3–19·7 | c.4·8 | 0·6 | 0·06 | 2 | 0·20 | 1·3 | | | | | | |
| 6 | Benin, S. Nigeria | Mid slope brown loamy sand over tertiary sands | 0–6 | 6·5 | | | 8 | 0·22 | 3·1 | 0·63 | | 22 | 280 | 1900 | 200 |
| | | | 6–12 | 6·2 | | | 3 | 0·12 | 1·5 | 0·25 | | | | | |
| | | **Ochrosols of Dry Forest and Savanna** | | | | | | | | | | | | | |
| 9 | Pokoase, Ghana | Upper slope brown loamy coarse sand over granite | 0–2 | 7·2 | 2·7 | 0·24 | 18 | 0·51 | 9·0 | 2·8 | 6400 | | | | |
| | | | 2–6 | 6·9 | 1·9 | 0·19 | 8 | 0·25 | 7·9 | 1·9 | | 32 | 410 | 5700 | 870 |
| | | | 6–12 | 6·9 | 1·2 | 0·12 | 3 | 0·17 | 5·9 | 1·4 | | | | | |
| 10 | N. Rhodesia | Clay loam | 0–1½ | 5·3 | 3·3 | 0·14 | | 0·33 | 2·3 | 0·07 | 2400 | | 637 | 510 | 17 |
| | | | 1½–12 | 4·9 | 1·0 | 0·05 | | 0·42 | 0·4 | 0·03 | | | | | |
| 11 & 12 | Ejura, Ghana | Upper slope reddish brown sandy loam over sandstone | 0–2 | 7·1 | 0·8 | 0·05 | 12 | 0·15 | 4·3 | 1·0 | 1600 | 20 | 170 | 2600 | 340 |
| | | | 2–6 | 6·9 | 0·7 | 0·04 | 5 | 0·12 | 3·9 | 0·7 | | | | | |
| | | | 6–12 | 6·4 | 0·4 | 0·03 | 2 | 0·09 | 2·3 | 0·53 | | | | | |
| 13 | Marandellas, S. Rhodesia | Loamy sand over granite | 0–9 | 6·5 | 0·46 | 0·05 | | | | | (2000) | | | | |
| 14 | Kpong, Ghana | Black, montmorillonitic clay over basic gneiss | 0–6 | 6·4 | 1·52 | 0·105 | 2·0 | 0·23 | 29·3 | 10·1 | 3300 | 4 | 290 | 25000 | 5100 |
| | | | 6–18 | 6·9 | 0·84 | 0·061 | 0·2 | 0·14 | 33·1 | 11·0 | | | | | |

Notes

Fallows 2 and 3. The soil under these fallows was not analysed. The figures for nutrients stored have been estimated by Bartholomew et al. (1953) from data on a similar soil elsewhere. For the whole of the Central Congo Basin Tondeur (1956) reports that top soils usually fall in the range: pH 4·1–4·5, C 1–2%, total cations rarely exceeding 2 m.e. per 100 g, Ca being 70–80% of the total, K and Mg c. 0·1 m.e. per 100 g. On this basis the total potassium stored in the 0–12 in. layer would be only about 100 lb.

Fallow 9. Data for 15 profiles in the Copperbelt region under Miombo are given by Ballantyne (1956). All are low in nutrients, and the example given is in the middle of the range. The low value of the exchangeable Mg is especially noteworthy, the median value for the immediate subsurface horizon (c. 2–10 in.) being 0·07 m.e. per 100 g.

*See footnote on p. 26.

## TABLE 4

**Nutrients Removed in Harvests of Common Native Crops**

| Crop | Yield | N | P | K | Ca | Mg | Authority |
|---|---|---|---|---|---|---|---|
| | | lb. per acre | | | | | |
| Maize (grain only) | 1,000 | 15 | 2·7 | 2·7 | 0·2 | 1·0 | Morrison (1954) |
| Rice (Paddy) | 1,000 | 12 | 3·2 | 3·5 | 0·8 | 1·4 | ,, ,, |
| Groundnuts (kernels) | 500 | 25 | 2·2 | 2·7 | 0·3 | 0·9 | ,, ,, |
| (shells) | 200 | 2 | 0·2 | 1·6 | 0·6 | | |
| Total | 700 | 27 | 2·4 | 4·3 | 0·9 | | |
| Cassava (fresh tubers, 30% dry matter) | 10,000 | 22 | 3·0 | 58* | 5·4† | | Imperial Bureau (1936) |
| Yam (fresh tubers, 30% dry matter) | 10,000 | 34 | 2·7 | 35 | 0·6 | | ,, ,, (1936) |
| Bananas (fruits, 30% dry matter) | 10,000 | 22 | 4·1 | 55 | 0·6 | | ,, ,, (1936) |
| Cocoa (beans) | 500 | 12 | 3·0 | 10 | | | Adams and McKelvie (1955) |
| (husks) | 500 | 10 | 1·0 | 22 | | | |
| Total | 1,000 | 22 | 4·0 | 32 | | | |

It is assumed that all other residues are left on the land

*Morrison's figure gives 33 lb.

†Another determination gives half this amount.

the particular patch of fallow cleared, though the application of the data depends on how widely representative was the fallow sampled. The indirect, easier, and more approximate method is to sample the main organs of the principal individual species in the fallow, arrive at a mean value and then use data which are often available from foresters on the weight of timber and brushwood in fallows of different ages or densities to obtain an approximate estimate of the nutrients stored in any given example. Strictly, of course, mean composition weighted according to the frequency of the species should be used, but in fallows with no marked dominants the mean lies close to the weighted mean. The sampling of grassland is a much simpler task, and calls for no discussion here.

Values for the nutrient composition of vegetation can only be applied to regions of similar soil composition. Though soils differ markedly from point to point over a short distance because of irregularities caused by termite mounds, fallen trees, etc., the average composition of larger areas, of the order of an acre, does not vary anything like so widely. Thus, soils are often sufficiently similar in their nutrient composition over wide areas to make generalization possible.

Part of the lack of appreciation of the relative importance of soil and vegetation as storehouses of nutrients, apart from the very scattered data, is due to the fact that soil analyses are usually reported as milliequivalents per 100 g. while amounts and analyses of vegetation are expressed in a wide variety of units. In this account all original data have been reduced to lb. per acre of the nutrient element. For the soil it has been assumed that the 0–12 in. layer, the 'top soil', weighs 4 $10^6$ lb. per acre. The limit of 12 in. has been chosen, firstly because the limit of the visible humic horizons usually lies between 8 and 12 in. and secondly because numerous observations of root distributions and direct measurements of labelled-phosphorus uptake (Nye and Foster, 1960) indicate that in humid regions nearly all the feeding of the annual crops which replace the fallows takes place within this zone. It is with the fertility of this zone that we are primarily concerned. In drier regions, where crops depend more on water stored at depth, subsoil nutrients may contribute relatively more.

### (a) Nutrient Content of Fallows

#### 1. *Moist Evergreen-Forest Zone*

No data are available for virgin moist evergreen forest, but Greenland and Kowal (1960) have measured directly the nutrients in all the component parts of mature well mixed secondary forest estimated to be 40 years old at Kade, Ghana (65 in. p.a.) in the ecotone between the moist evergreen and moist semi-deciduous forest (example 1). The basal area at breast height of this forest was 145 sq. ft. per acre, which is the same as the value attained by

very old or primary tropical high forest (Dawkins, 1958). The soil was an oxysol-ochrosol intergrade developed from phyllite.

Valuable data on younger secondary forest are available as a result of the pioneering work of Bartholomew, Meyer and Laudelout (1953) at Yangambi in the Belgian Congo under a rainfall of 73 in. p.a. on an intensely leached reddish yellow latosol (Kellogg and Davol, 1949). Here, as over most of the Central Congo Basin, the forest fallow is dominated by the Umbrella Tree, *Musanga cecropioides*, for at least the first 15 years. Bartholomew *et al.* undertook the formidable task of measuring the nutrients stored in different parts of forest fallows of varying ages up to 18 years. A selection from their data is given in examples 2 and 3. It will be noted that the storage capacity of leaves and litter is reached at an early stage, and thereafter the total storage increases more slowly, and in the woody material only. *Musanga cecropioides* is relatively rich in potassium which accounts for the high storage of K in the early years. Other examples of mixed forests presented here (Nos. 1, 4, 5) have a lower percentage of K and a higher percentage of Ca and Mg in comparable organs.

2. *Moist Semi-Deciduous-Forest Zone*

No direct measurements have been made of the nutrients stored in mature, moist semi-deciduous tropical forest. An approximate estimate may, however, be formed by combining Lebrun's (1934*a*) measurements of 400–600 cu.m. per hectare (5800–8700 cu. ft. per acre) of timber in the 'equatorial' forest of the Belgian Congo with the average of the compositions of the stemwood of 67 species and the bark of 19 species of trees in the forest of the Mayumbe district (c. 50 in. p.a.) of the lower Congo, listed by Istas and Raekelboom (1952), (example 4)*. The data of example 1 have been used to

* More recent unpublished measurements of the volume of wood in tropical forest are available from the Belgian Congo and the French Ivory Coast. The Forestry Division of I.N.E.A.C. (private communication by Director General) has obtained the following figures.
For one hectare of *Scorodophloeus Zenkeri* of mixed age

| | |
|---|---|
| Trunks .. .. .. | 309 cu.m. |
| Large branches .. .. | 92·5 „ |
| Small branches and twigs .. | 210 „ |
| Total | 611·5 cu.m. (equivalent to 8900 cu. ft. per acre) |

For the total volume of wood in trees over 20 cm. in circumference in natural secondary forest of *Musanga cecropioides*, *Macaranga lancifolia* and *Caloncoba welwitshii* 94 cu.m. at 4 years, 225 cu.m. at 7 years, and 214 cu.m. at 9 years.

P. Bellouard, Conservator of Forests A.O.F., (private communication) has measured the total volume of all woody material in the forest of Téké, French Ivory Coast, (rainfall c. 80 in. p.a.) on an area of 4 hectares completely cleared. He obtained 250–300 cu.m. per hectare (3600–4300 cu. ft. per acre). The forest was primary and its density representative of the primary forest in the Ivory Coast under this high rainfall. From his own observations, the primary forest of the Belgian Congo is much denser.

estimate the contribution of trash and litter to the total. The example is most useful in showing that the composition of the wood plus bark in this forest is very similar to that of the moister forest at Kade. The richness of the bark compared with the wood, especially in calcium, is notable.

For secondary forest in this region the figures are available of the average nutrient composition of 14 of the predominant species in a mixed fallow about 20 years old at Kumasi (60 in. p.a.) in Ghana (Nye, 1958). By combining these with the weights of the 18-year secondary forest in the Congo the approximate amounts of nutrients stored can be estimated (example 5). The composition of the wood plus bark agrees well with that obtained in the lower Congo—example 4.

An example, No. 6, of a shorter fallow in this region comes from Benin, (72 in. p.a.) Southern Nigeria (Nye and Hutton, 1957). It consists entirely of *Acioa barteri*, which here was deliberately planted, but is well known as a natural thicket as well as a planted fallow in many parts of south-eastern Nigeria for its ability to thrive and restore fertility on exhausted soils.

The composition and storage capacity of woody fallows in the moist forest region may be compared with that of a fallow of elephant grass, which is the most vigorous grass in regions with a closed forest climax. It dominates wide areas of southern Uganda as a 'derived' savanna. The example quoted (example 7) comes from a planted fallow in a fairly high-rainfall area (70 in. p.a.) at Bambesa in the Belgian Congo (Laudelout, Germain and Kesler, 1954). Productivity and N content may not be so high in the long-established *Pennisetum* grasslands. It will be seen that the grass compares very favourably with short-period woody fallows of up to 5 years in its storage of all nutrients except Ca.

It is of interest to compare the amount of nutrients in tropical forest with the average amounts of nutrients stored by pure stands of temperate hardwoods after 100 years' growth (17 examples covering 8 species), which have been compiled by Rennie (1955) (example 8). The average mature equatorial forest of the Congo and Ghana contains about 30 per cent greater weight of vegetation than the average even-aged 100-year-old temperate hardwood forest. Largely because its wood is richer it contains very much more P, K and Ca.

3. *Dry Deciduous-Forest Zone*

No data are available for the climatic-climax vegetation in this zone.

In the secondary Guinea Coastal Thicket widespread in south Ghana under c. 40 in. p.a. data are available for the yield of cord wood at 10 years and the average composition of mature leaves and stems of 14 species (example 9) (Nye, 1958). It may be noted that growth in this 10-year-old dry thicket is less than in the 5-year-old

moist secondary forest of the Congo. Storage of N and K is also less, P comparable, and Ca and Mg greater. The higher levels of Ca and Mg are due to the difference in species in the fallow, and to the improved status of Ca and Mg in the soil under this lower rainfall.

It has been possible to form an estimate of nutrient storage in the widespread *Isoberlinia-Brachystegia* (Miombo) woodland by combining Brockington's (1956) estimate of a 'good' yield of 30 cords (approx. 2250 cu. ft.) of firewood per acre in the Rhodesian Copperbelt (rainfall c. 50 in. p.a.) with the composition of the wood from the same region given by Young and Golledge (1948) (example 10). The contributions of the leaves and twigs and the herb layer will not increase the amount stored by more than one third.

This example is particularly interesting because of the 'chitemene' system (see p. 17) practised in this type of woodland. In western Lala, Northern Rhodesia, for example, Wood (1949) finds the area from which branches are lopped is 11 times the area on which they are piled and burned. Even if only half the standing woodland is lopped the cultivated plot will be enriched by very considerable quantities of nutrients, exceeding the amounts added to land under high forest when this is cleared and burned.

In the high-grass savanna, which is by far the most extensive formation in this zone, the nutrients stored in the vegetation depend very largely upon the extent to which trees and shrubs have been destroyed. The grasses and herbs themselves store relatively small quantities of nutrients. This is illustrated in example 11 taken from the high-grass savanna under Andropogoneae at Ejura (59 in. p.a.) north of the closed forest in Ghana, in a representative area undisturbed for over 20 years, under approximately $\frac{1}{4}$-closed tree canopy, (16 cords per acre = approx. 1200 cu. ft.) at the end of the growing season (Nye, 1958). It will be noted that the composition of the savanna trees is similar to those of the forest except that the nitrogen content of leaves and wood is only about half. This accords with the low status of available nitrogen under the high grasses of this type of savanna (see p. 109). In the same area a plot devoid of trees, dominated by *Imperata cylindrica* was sampled (example 12). The considerable weight of stolons and the large proportion of the nutrients stored in them are notable features of this example.

### 4. *Deciduous-Thicket Zone*

No data for the climatic-climax thicket are available, though the data for the secondary Guinea Coastal Thicket should be comparable.

For the tall bunch-grass of this zone, the figures for natural veldt at Marandellas, Southern Rhodesia, are included to illustrate the very low storage capacity of the natural grassland in regions with rainfall below 35 in. p.a. (example 13) (Weinmann, 1948).

(b) Nutrient Content of Soils

The analyses of the acid soils of the moist evergreen forest (examples 1–3, Table 3) reveal the striking fact that the amounts of all exchangeable nutrients, except phosphorus, in the top 12 in. of soil are considerably less than the amounts stored in mature-forest fallows. The soil under the 40-year forest (example 1) was an oxysol-ochrosol intergrade, and as such much richer in calcium and magnesium than the true oxysols. More representative data for the oxysols are derived from Reed's (1951) survey of over 100 profiles developed over basement-complex rocks in Liberia under a rainfall of 80–180 in. p.a. The average for this data is given as Example 1A.

The soils under the fallows at Yangambi in examples 2 and 3 were not analysed, and the figures quoted are based on a single profile. Data more representative of the soils of the Central Congo Basin which are developed over poor sedimentary formations are mentioned by Tondeur (1956) (see foot of Table 3).

For the moist semi-deciduous-forest zone the figures for ochrosols in examples 5 and 6 are fairly typical, but to establish the nutrient status of the soils on a broader basis the average figures for a range of 51 forest profiles in the mixed semi-deciduous forest of Ghana (de Endredy and Montgomery, 1954) (example 5A) are also quoted. The notable difference from the oxysols is the great increase in Ca and Mg. Consequently, the Ca and Mg in exchangeable form in the soil now exceed the amounts stored in secondary forest vegetation under 20 years old, and are comparable with the amounts in mature high forest. The exchangeable K and available P remain comparable with amounts in the younger secondary forest, but are less than the amounts in mature high forest.

It is natural and right that in the high-rainfall regions with excessively leached soils the role of the vegetation in storing nutrients and preventing their loss by leaching should be emphasized. However, the reaction against the earlier view of the richness of the soil under luxuriant tropical forest has now swung to the other extreme, and the current fashion is to condemn tropical forest soils in general as being of most ephemeral fertility, ignoring the great difference between the poor soils of the moist evergreen forest and the richer soils of the moist semi-deciduous forest, e.g. Gourou (1953). The critical paper by Vine (1954), aptly entitled "Is the lack of fertility of tropical African soils exaggerated?" is a useful corrective.

Beyond the boundaries of the moist forest, analyses of soils under secondary formations of thicket, woodland and high-grass savanna must be interpreted with caution because there are not large numbers of examples, and because the depredation of the vegetation may be so recent that the soil still bears the impress of a former more vigorous forest vegetation.

In general, the amounts of nutrients stored in the surface horizon of those soils are less than in the same horizon of soils under moist semi-deciduous forest owing to a lower level of organic matter

(examples 9. 10. 11). The sub-surface horizons do not differ so greatly, and the nutrients stored in the top foot are not markedly less. In still drier regions, such as those under tall bunch-grass savanna, organic-matter levels and nutrients stored are still lower (example 13).

In all these examples the soils have been kaolinitic. In the much less widely distributed rubrisols, brunosols and black earths that may be developed over basic rocks the amounts of Ca and Mg stored in the soil are very much greater owing to the presence of 2 : 1 lattice-type clay minerals. The amounts of N, K and P are not necessarily higher. The analysis of a black montmorillonitic clay developed on a gentle hill slope, supporting high-grass savanna under a rainfall of 43 in. p.a. at Kpong, Ghana (Brammer, 1955), (example 14) illustrates this point.

Comparing now the amounts of nutrients in the vegetation and soil, we find that well developed thicket and Miombo Woodland store considerably less Ca and Mg than the top foot of soil, but amounts of P and K comparable to the readily available amounts in the exchangeable pool. The high-grass savanna, if well wooded, may also store as much P and K as the top foot of soil, but where trees and shrubs are sparse the savannas store far fewer of all nutrients than the soils supporting them.

## Chapter 3

## THE NUTRIENT CYCLE

Having established the amounts of nutrients in the soil and fallow we now have to consider how rapidly the interchange between them takes place. Knowledge of this nutrient cycle is an essential background to an understanding of the way in which the fertility of the top soil is restored during the fallow period. In addition to evaluating movement of nutrients within the soil-vegetation system, we have also to determine how important are losses from the system by drainage and, for nitrogen and sulphur, by volatilization, as well as gains to the system from the atmosphere.

The complete cycle, together with the loss and gain processes, are illustrated in fig. 1. In discussing the cycle we shall consider firstly the transfer of nutrients between the soil and vegetation, secondly movement of nutrients between different soil horizons, and thirdly the losses from and gains to the soil-vegetation system.

### I. Transfer of Nutrients between Soil and Vegetation

The processes concerned in this type of transfer are (a) uptake by the vegetation, (b) removal from the vegetation and return to the soil, as litter, in rain-wash, by burning and in root excretions.

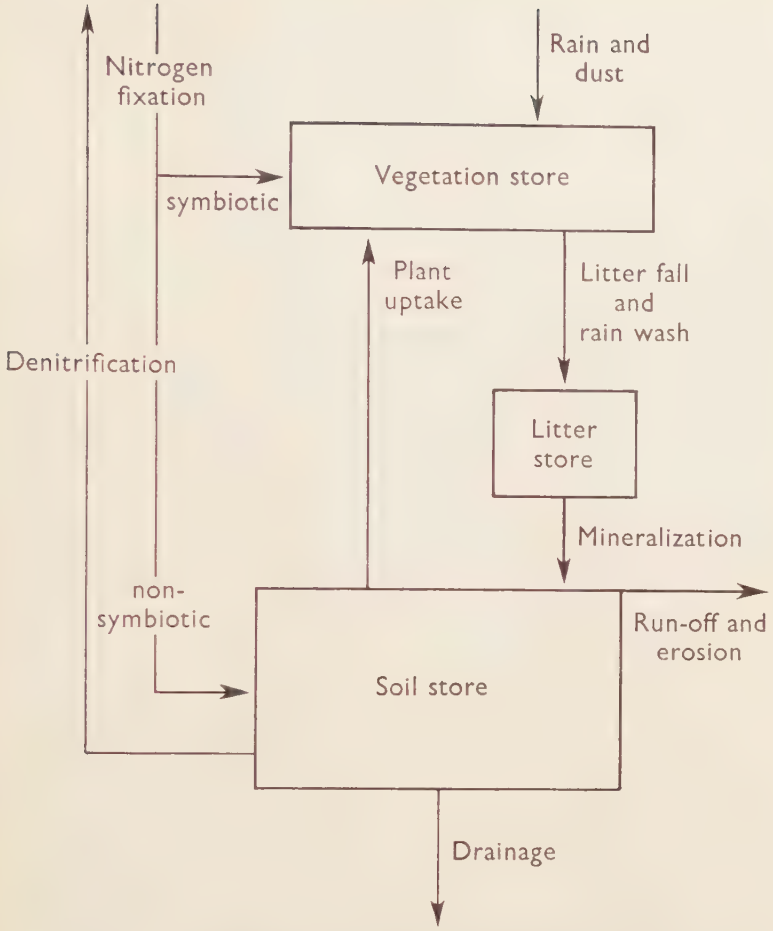


Fig. 1. The Nutrient Cycle between Soil and Forest Fallow

Further, as litter fall does not add nutrients as such to the soil a further process, (c) mineralization of litter, is involved. We shall consider each of these in turn, and endeavour to give quantitative figures for the amounts of nutrients involved in each process.

(a) *Uptake by the Vegetation*

The total rate of uptake of nutrients (in excess of any that may be excreted back to the soil through the roots) is equal to the increase in storage in the vegetation plus the amount removed from the vegetation. The removals are considered under (b). Typical figures for the annual increase in storage in forest vegetation including roots can be obtained from the data of Bartholomew *et al.* (1953) for forest

fallows of up to 18 years of age at Yangambi, and from the data for 40-year-old forest at Kade (Greenland and Kowal, 1960). These are collected below.

Mean Annual Increase in Vegetation Storage (lb./acre)

| | N | P | K | Ca | Mg | Forest |
|---|---|---|---|---|---|---|
| Over first 5 years | 102 | 5·6 | 81 | 75 | | Yangambi |
| Over first 18 years | 35 | 5·3 | 30 | 41 | | Yangambi |
| *Over first 40 years | 36 | 2·5 | 15 | 48 | 6 | Kade |
| Over first 4 years (excluding roots) | 42 | 3·0 | 31 | 39 | 9 | Coastal thicket, Pokoase (Nye, 1958). |

* Storage in two very large trees, already standing when the forest regenerated, has been excluded.

It is seen that accumulation during the first five years of growth is more rapid than during the later periods. The reason for the change after the first 5 years, and the subsequent relatively slow increase in storage, is that the leaves and twigs, which are richer in nutrients than other components of the vegetation, rapidly increase to their maximum amount in the fallow, and further storage takes place in the wood and roots. Thus with the exception of P, over half the nutrients stored in the 18-year-old fallow in the Congo had been accumulated by the 5-year-old fallow. It is possible that the difference in the case of P is due to sampling errors since the phosphorus composition of the wood of the 18-year-old fallow, 0·05%, seems high. It will be seen from the data discussed under (b) that the annual increase in storage in the vegetation after the first five years is a relatively small proportion of the total annual nutrient uptake by the vegetation.

The actual uptake and storage may differ somewhat from the figures quoted, particularly if the land is cultivated for more than the usual two to three years, for prolonged cultivation reduces the number of stumps, roots and viable seeds in the ground from which the vigorous regrowth of natural vegetation normally develops. Long-continued cultivation or the incidence of severe erosion might also reduce soil fertility sufficiently to limit the vigour of the regrowth of vegetation. Such an occurrence must however be regarded as exceptional; in all normal circumstances regrowth is, as a matter of experience, extremely rapid and vigorous, and the figures given may be taken as typical of the nutrient absorptions normally occurring.

For the savanna zones it is not easy to obtain a figure for the rate of increase of storage in the vegetation. The annual grass burn causes the return of all nutrients taken up by the grasses to the soil, except the nitrogen and sulphur. Tree density is extremely variable and the age of trees extremely difficult to judge. Tree growth is certainly slow, being severely restricted by fire, and probably by shortage of available nitrogen induced by the grasses. It is therefore impossible to give any meaningful figure for the annual increase of

nutrients stored in the trees. It will obviously be much less than the uptake by forest vegetation, and in general it seems unlikely that it will be significant compared with the total uptake. The last example in the table shows that in unburnt thicket vegetation the rate of increase of storage is somewhat less than in young forest vegetation.

(b) *Removal from the Vegetation*

This includes litter fall, rain wash, burning and root excretions. Information on the production of litter and its nutrient content is given in Table 5. They are readily measured by collecting the litter over a period and weighing and analysing it. In moist tropical forest the production amounts to about 5 tons of dry matter per acre, which compares with an average figure of a little over 1 ton per acre in temperate hardwood forests. In the savanna nearly the whole of the herb growth during the rainy season is burnt before the beginning of the following rains. From Table 2, example 11, it will be seen that the material burnt amounts to 3–4 tons per acre in the high-grass savanna. All nutrients except N and S are returned to the soil in the ash. Example 11 also shows that the additional contribution from the leaf fall of the trees will usually be small. In closed Miombo woodland, however, it is possible that figures approaching those quoted for temperate woodland are achieved.

The nutrient content of the litter has generally been taken as a measure of the annual nutrient turnover. However, litter as usually collected in trays consists only of leaves, twigs and small wood. In young forest fallows this is a fairly accurate measure of the return to the soil, but in older fallows some allowance must be made for the fall of branches and stems. This may be estimated in a mature forest fallow by assuming that the annual timber fall is equal to the annual production of wood. Weck (1956) gives an average value for the latter of 10,000 lb. dry wood per acre. This estimate accords well with the annual increase in weight of the fallows for which data were given in Table 2, if some allowance is made for fall of timber during their growth.

Data for the complete nutrient cycle in the 40-year-old forest at Kade are presented in Table 6. The nutrient composition of the timber fall is assumed to be the same as of the dead wood. It will be seen that the effect of timber fall is to increase the turnover of nutrients estimated from litter alone by substantial amounts, especially of calcium (Nye, unpublished).

Another source of nutrient cycling is washing of nutrients from the leaves by the rainfall. It has for many years been recognized that the washing of nutrients from the leaves of crops by rainfall may be an important source of loss from growing vegetation. The extent of the losses reported varies widely according to the treatment of the plants. Mes (1954) and Stenlid (1958) have reviewed the subject. Unfortunately little work has been done with intact growing

## TABLE 5

### Rate of Litter Production (per annum)

| Vegetation | Place | Litter Fall (lb./acre) | Nutrients in Litter (lb./acre) | | | | | Authority |
|---|---|---|---|---|---|---|---|---|
| | | | N | P | K | Ca | Mg | |
| Forest (Musanga dominant) | Congo | 13,000 (dry matter) | 125 | 4 | 93 | 111 | 38 | Laudelout (1954) |
| Mixed Forest | ,, | 11,000 (dry matter) | 200 | 6 | 43 | 94 | 46 | ,, ,, |
| Mixed High Forest | Ghana | 9,400 (oven dry) | 178 | 6·5 | 61 | 184 | 40 | Nye (unpublished) |
| Rain Forest | Colombia | 7,000 (oven dry) | | | | | | Jenny (1950) |
| ,, ,, | ,, | 9,100 (oven dry) | | | | | | ,, ,, |
| ,, ,, (Sub-tropical mixed spp.) | Queensland | 6,000 (oven dry—leaf only) | 96 | 5 | 33 | 67 | | Webb (1956) |
| Temperate Hardwoods | New York | 2,700 (dry matter) | 17 | 3 | 14 | 66 | 9 | Chandler (1941) |

TABLE 6

**Nutrient Cycle in High Forest at Kade, Ghana**

| | Wt. of material (oven dry) | Nutrient elements (lb./acre/annum) N | P | K | Ca | Mg |
|---|---|---|---|---|---|---|
| Rainfall in open— (73 in. in 12 months) | | 13 | 0·4 | 16 | 11 | 10 |
| Rainfall under forest— (62 in. in same period) | | 24 | 3·7 | 212 | 37 | 26 |
| Rain wash from leaves | | 11 | 3·3 | 196 | 26 | 16 |
| Timber fall | 10,000 | 32 | 2·6 | 5 | 73 | 7 |
| Litter fall (on 12 months' records) | 9,400 | 178 | 6·5 | 61 | 184 | 40 |
| Total addition to soil surface | | 221 | 12·4 | 262 | 283 | 63 |

plants. Tamm (1953) found nutrient losses from 6 broad-leaf deciduous trees in Sweden averaged 12 lb. K, 0·6 lb. Ca, 1·0 lb. Na per acre following a period in which 9 in. of rain fell. Ingham (1950) has measured the composition of rain water collected beneath a tree on the coast of Natal and in the open during a year in which 49 in. of rain fell. He found that the equivalent of 240 lb. Ca and 9·4 lb. P per acre were added to the surface soil under the tree. He attributed these amounts to the washing away of water-soluble "aerosols" adsorbed from the air by the leaves. His results are unlikely to be applicable to inland areas. Results which have been obtained under the forest at Kade, which is 60 miles from the sea, are shown in Table 6. In comparison with amounts in the litter, remarkably large quantities of potassium and phosphorus, but only small quantities of nitrogen, calcium and magnesium are washed out of the leaves. These findings, which agree in general with earlier work on this subject, establish for the first time the relative importance of rain wash and litter fall for the major nutrients under forest.

The total annual nutrient uptake in the 40-year-old mixed secondary forest at Kade is shown in Table 6. It may be calculated from data in Table 2 and 6 that the annual turnover of nutrients expressed as a percentage of the total capital stored in the vegetation is as follows: N 11%, P 11%, K 32%, Ca 12%, Mg 18%. Of course, in younger forest the turnover is a greater proportion of the storage.

In savannas the annual uptake by grasses is nearly equal to the nutrients stored at the end of the growing season, before serious leaf fall occurs. No data are available for the vigorous natural elephant-grass savannas, but a planted plot at Bambesa, Belgian Congo in the first year of growth produced per acre 26,000 lb. of dry matter and took up 248 lb. N, 20 lb. P, 43 lb. S, 41 lb. Ca, 78 lb. Mg and 275 lb. K (Laudelout, Germain and Kesler, 1954), a performance which compares well with the mature high forest for all nutrients except Ca. We do not know whether this rate of uptake is

sustained in older fallows. In the fire-climax high-grass savanna of Andropogoneae, the rate of uptake is much lower, as shown by the figures in Table 2 (example 11). Nye (1958) has given some data indicating that the uptake in the earlier years of such a fallow may be about 50% greater, increasing shortage of nitrogen limiting growth in later years.

A matter requiring further attention is the effect on the soil of the very much greater proportion of Ca and Mg to K circulating under a forest fallow than under a grass fallow. Preliminary indications are that the exchangeable K/Ca ratio in the topsoil is increased by the growth of a grass rather than a broad-leaved fallow (e.g. Nye and Hutton, 1957), and this improvement in the potassium status of savanna soils agrees with their general lack of response to potassium fertilizers, in contrast to the forest soils. The high proportion of non-exchangeable potassium in savanna soils may also be due partly to the grass vegetation as well as to unweathered minerals.

(c) *The Rate of Mineralization of the Litter*

When the litter under a woody fallow has been built up to its maximum level, the rate of mineralization clearly equals the rate of addition. Under tropical conditions this level is rapidly attained, and possible increase in storage of nutrients in the form of litter need hardly be taken into account after a few years of fallow. Greenland and Nye (1959) calculated from the data of Jenny et al. (1949) that when the litter layer had attained its maximum or equilibrium level, 3·25% decomposed in one week, or over one year the amount of litter decomposing was 170% of that found on the forest floor at any one instance. This very high rate of decomposition is to be expected when the annual litter fall is about 5 tons per acre, and the level of litter on the forest floor rather less. The rate at which the maximum level of litter on the forest floor will be attained will also be very high—between one and three years for most tropical forests.

The maximum level of individual nutrients stored in the litter will be even more rapidly attained. The ones that are leached most readily will reach this level most quickly. Bartholomew et al. (1953) have shown that potassium is lost very rapidly from fresh forest litter. After 10 weeks 51% of the N, 61% of the P, 93% of the K, 50% of the Ca, and 82% of the Mg in the original litter had been mineralized. Conversely, reference to Table 2 will show that the ratio Ca/K in the litter of all the forest examples is considerably greater than in the fresh leaves or wood.

## II. Movement of Nutrients within the Soil

Thanks to the writings of Hardy (1936), Milne (1937) and others it is now well known that in a soil under mature forest the nutrients are maintained in a nearly closed cycle from which few nutrients

are lost in the drainage. The downward movement by leaching is nicely balanced by the upward movement into the plant and eventual return to the soil's surface, as well as by the husbanding of a large part of the nutrient reserve in the living vegetation.

The details of this nicely adjusted balance are, however, little understood, and it has even been stated that no downward movement of nutrients occurs under virgin forest. It may be well therefore to examine a little more fully the counterbalancing processes of leaching and uptake, even though quantitative detail is lacking.

(a) *Leaching*

So long as there is percolation down the profile and there are nutrient ions in the soil solution these will be leached. The main anions in the soil solution are $NO_3^-$, $SO_4^{=}$, $Cl^-$, $HCO_3^-$. In the slightly acid and acid topsoils such as we are dealing with, the nitrate ion and to a lesser extent the bicarbonate ion are quantitatively the most important. These are little adsorbed by the soil, so that nearly all are in the soil solution. There they are balanced by cations, the most important being $Ca^{++}$, $Mg^{++}$ and $K^+$. $H^+$ plays a very minor role, as also does $Al^{+++}$, except in very acid soils. It must be appreciated that the total concentration of cations in the soil solution depends on the total concentration of the anions. In particular, a high level of 'biological activity' in a soil, leading to a high level of nitrate ion, implies a corresponding concentration of nutrient cations in the soil solution and therefore ready leaching.

The rate of leaching of a nutrient at any point in the profile will be the product of its concentration in the soil solution and the rate of percolation. Actively growing vegetation reduces leaching losses by

(a) transpiring water and so reducing percolation;
(b) absorbing anions, especially nitrate, from the soil solution;
(c) repressing nitrification (a process extremely important in grasslands) and so reducing the concentration of anions that would otherwise occur.

Here we may note that the leaching of cations is not directly countered by their uptake, but only indirectly, by removal of anions from the soil solution. If a cation alone were taken up from the soil solution, it would simply be replaced by another from the well buffered exchange complex.

There is no direct evidence of the amount of nutrients being leached from one horizon to another under natural forest, and until lysimetry techniques improve it will be very difficult to obtain this information. Joffe (1932), for example, has attempted such measurements under temperate woodland, using small Ebermayer-type lysimeters, but Kohnke et al. (1940) in a critical review consider the very low percolation figures obtained by this method are due to the drainage water flowing round the collecting funnels. The suction-plate method described by Cole (1958) promises to be much more

satisfactory. A particular difficulty associated with tropical soils is the possible occurrence following heavy storms of lateral drainage through the permeable surface layers above the more compact subsoil. Losses by surface run-off under forest are probably small.

This discussion has been centred on the nutrient cations. The phosphate ion is most unlikely to be leached in significant amount beyond the top few inches. The phosphorus concentration of the soil solution in equilibrium with forest subsoils in tropical Africa is usually immeasurably low; so that any phosphorus leached would be adsorbed. Phosphorus is only found in the percolate of lysimeters when high applications of phosphate are made to very light soils.

(b) *Uptake*

Though the total rate of uptake of nutrients can be measured, as we have shown, it is impossible to measure by normal methods the proportion drawn from the different soil horizons. Even were it possible to follow the changes in composition of each horizon during a fallow period, uncertain nutrient changes by addition from litter and leaching take place at the same time. In forest, the distribution of the roots suggests that the great preponderance of feeding occurs in the top soil. It is well known that the enormous buttressed trees of the high forest have shallow root systems and no tap root (Richards, 1952), and it is only the unbuttressed trees, largely understorey species, that have tap roots (Donis, 1948; Foggie, 1957). Jones (1955) has observed in the Nigerian rain forest that the root distribution is similar to that which would be seen in similarly well drained English soils. In the 40-year-old forest at Kade, Greenland and Kowal (1960) found 86% of the roots were in the top foot. The corresponding figure for 15-year-old fallow was 80%. In an 8-year-old forest fallow at Yangambi, dominated by *Musanga cecropioides*, 68% of the roots were in the top 10 inches (results of W. V. Bartholomew quoted by Greenland and Kowal, 1960). It is possible that these figures based on total root weight overemphasize the percentage of the total root-absorbing surface found in the top soil, since this contains a greater proportion of large roots.

In savanna, our general observations are that the range of root systems in the trees is similar to that of the smaller forest trees. Rawitscher (1948) has noted some savanna plants with very deep-rooting systems in the savanna of southern Brazil, and Ferri (1959) found these plants transpired freely through the dry season.

For grasses Laudelout, Germain and Kesler (1954) found among a wide range of species planted in a free-draining soil at Yangambi (73 in. p.a.) that well over 50% of the roots of nearly all species are in the top 8 in. In the natural high-grass savanna dominated by *Schizachyrium semiberbe*, for which data are given in Table 2, Nye (1957) found 30 times as much root in the 0–6 in. as in the 6–12 in. layer of the free-draining sandy soil. In the Transvaal high veldt

Coetzee et al. (1946) record over 50% of the roots in the top 4 in. and over 70% in the top 8 in.

Not only are there few roots in the subsoil, but their activity there may well be lower than in the topsoil because of poorer conditions for feeding. In general the subsoil is much more compact than the topsoil, and the availability of phosphorus and calcium falls away sharply. Use of $P^{32}$ showed that high-grass fallow derived about 30% of its P from layers below 10 in. containing 19% of the roots (Nye and Foster, 1960).

Though the proportion of subsoil feeding may be small it is very important, for it is from this source together with rain and dust fall that losses in 'total' nutrients from the top soil by leaching and cropping are made good. That it occurs to a significant extent is indicated by the fact that the totals of relatively immobile nutrients such as phosphorus and calcium in tropical forest soils are nearly always greater in the topsoil than the subsoil (Nye (1957) for phosphorus, Baley and Chezeau (1954) and Leneuf (1956) for calcium). If 20% of the total uptake calculated in Table 6 for a mature high forest is drawn from below the first foot it represents amounts of 36 lb. N, 2·5 lb. P, 52 lb. K, 55 lb. Ca and 11 lb. Mg per acre "pumped up" per annum. The performance of younger forest fallows should not be much less, since their root system is already established for the suckering species, and their foliage rapidly forms a dense canopy.

It will be noted that on this basis the uptake from the subsoil is about equal to, and for potassium greatly exceeds, the annual increase in storage in the fallow, shown on p. 36. Further evidence that subsoil feeding is sufficient to supply the vegetation store and may also increase the nutrient content of the top soil during the fallow period is given in the next chapter.

## III. Losses from and Gains to the Soil-Vegetation System

The loss processes operating are leaching of nutrients out of the rooting zone of the vegetation, removals in run-off water, volatilization of nitrogen through the activity of denitrifying organisms and volatilization of nitrogen and sulphur through oxidation when the vegetation is burnt. Gains consist of additions in rainfall, dust and fixation of atmospheric nitrogen by micro-organisms. The gains and losses of nitrogen due to microbial processes will not be considered here, as they are intimately involved in the carbon and nitrogen cycles considered in detail in the next chapter.

### (a) *Leaching and Erosion Losses*

An approximate upper limit to the amount of leaching and erosion that occurs from the plant-root zone under closed forest may be deduced from the nutrients carried by the River Amazon whose catchment is very largely under closed forest, most of it under rainfall exceeding 70 in. p.a. Russell (1950) calculates from Clarke's (1924) data that the drain of nutrients is 4 lb. K, 33 lb. Ca,

4·5 lb. Mg, 9 lb. Na, 0·4 lb. N (as $NO_3$), 10 lb. Cl, and 5 lb. S (as $SO_4^{=}$) per acre per annum. Most of the cations are balanced by the bicarbonate ion. The very low amounts of nitrate ion are particularly to be noted since, as will be seen, the nitrate ion is usually more important than the bicarbonate ion where leaching from the top soil under cultivation is concerned. The loss of cations by leaching from the actual solum will undoubtedly be less since some of the nutrients in the rivers will come from the deeper zones of primary weathering. Leaching from the solum could only exceed amounts carried away in the drainage system if there were substantial and increasing zones of accumulation of nutrients in the deep subsoil, and these have not been reported from closed-forest areas.

An estimate of the average composition of drainage waters from drier forest soils has been obtained by averaging the composition of 23 rivers draining the moist semi-deciduous forest of Ghana (50–70 in. p.a.) given by Dunn (1947). The composition in Ca and Mg is slightly lower than that reported by Clarke for the Amazon. No figures for K are given. Since under the lower rainfall the drainage will be less than in the Amazon basin, the figures given above may be considered as an upper limit for leaching and run-off losses in the moist semi-deciduous forest region as well.

It will be seen that the amounts of nutrients taken up from the solum and added to the surface each year (Table 6) greatly exceed the maximum losses from the solum by leaching and run-off. The nearly closed cycle of nutrients under tropical forest, with uptake by the vegetation preventing losses in leaching, appears to be borne out. Nevertheless it must be recognized that it is not only absorption into the vegetation and reduction of leaching through increased transpiration (compared with the soil under cultivation) which are responsible. These two factors may be important, particularly in the moist semi-deciduous-forest zone of relatively low rainfall (c. 60 in. p.a.) and neutral topsoils. Here the rainfall during the months when through leaching is liable to occur may be only slightly greater than the amounts of water lost by evaporation and transpiration under a full vegetative cover. In the moist evergreen forest, through leaching may be anything from 20 to 100 in. p.a. or more. Consequently increased transpiration is of relatively little importance. A factor which may be important in preventing further leaching losses is the inhibition of nitrification by the high acidity of these soils. We know little of actual nitrate levels under the forest but it seems likely that they will be low* (p. 108). The concentration of bicarbonate ion will also be very low, and consequently little loss of nutrients can take place because there are no anions to maintain significant concentrations in the soil solution.

Similarly in the savanna zone nitrification is repressed by the grasses, so that once a grass cover is established leaching losses

*Now confirmed experimentally (P.H.N.)

must again be low. Nitrification under forest and savanna fallows is considered in more detail in the next chapter.

The question of losses by erosion is considered in some detail in Part II. Under undisturbed forest and savanna these losses are small.

(b) *Gains from Atmospheric Sources*

The regions of shifting cultivation are remote from industrial districts, and any nutrients they receive directly from the atmosphere are derived primarily from the sea or fine ash from bush fires or dust from deserts. Nitrogen as already mentioned is a special case and we consider here only accession of the chemically combined forms.

Eriksson (1952) and Tamm (1958) have reviewed analytical data on rainfall collected from temperate regions. Much of the data deals with regions near the sea or industrial areas. A fair indication of amounts that might fall in tropical regions remote from the sea is possibly given by the annual supply of elements in rainfall in six agricultural districts of Sweden which is calculated from data given by Tamm as: $NH_4$-N 1·5, $NO_3$-N 0·7, K 2·1, Ca 5·3, Mg 1·2, Na 5·7, Cl 8·7, S 5·1 lb. per acre for an average rainfall of 21 in. The amount of P was not recorded in this series, but in another Swedish station it was 0·1 lb. per acre per annum. The amounts collected at Kade shown in Table 6 agree approximately with these results if allowance for a rainfall of 70 in. is made. Numerous estimates assembled by Eriksson, of nitrate N and ammonium N falling in tropical regions, have a median of 7 lb. N per acre per annum.

All the nutrient cations added to the soil in the rain cannot be regarded as an effective gain. A high proportion are balanced in the atmosphere by $Cl^-$ and $SO_4$ anions. These anions are but weakly adsorbed by the soil colloid and therefore increase the concentration of the soil solution. When they are leached an equivalent quantity of nutrient cations is lost with them.

It seems likely that in a great area such as the Amazon basin containing for long ages mature soils under high forest, the annual exports of $Cl^-$ and $SO_4^=$ in the drainage waters represent the amounts of $Cl^-$ and $SO_4$ added from atmospheric sources plus any small additions from rock decomposition. From figures already quoted this would put the maximum addition of these anions as 10 lb. $Cl^-$ and 5 lb. S as $SO_4^=$ per acre per annum.

The amounts of aeolian dust deposited on vegetation have not been estimated in the tropics. From the figures for Europe quoted by Tamm (1958), 100 lb. per acre is a high figure except on the fringe of desert areas. Doyne et al. (1938) report that a sample of 'harmattan' dust derived from the Sahara and collected in Northern Nigeria contains no $P_2O_5$, 1·62% $K_2O$, 5·28% CaO, 2·07% MgO, 0·80% $Na_2O$.

The main conclusions of this chapter are as follows:—

The rate of turnover of the elements in the nutrient cycle under

forest fallow is very rapid and after the first few years greatly exceeds the rate of storage in the fallow. In addition to the quantities of nutrients in the litter fall, important amounts of potassium and phosphorus are washed out of the leaves of the vegetation. In older fallows significant amounts of calcium are contained in falling dead wood. The annual addition of dry litter under forest is around 10,000 lb. per acre. It decomposes very rapidly; consequently, the litter layer is thin.

The addition of nutrients in the form of rain and dust fall is very small in comparison with their rate of cycling. Estimates of nutrient losses from the solum are scarce, but in mature forest soils may be little more than the amounts added in the rain and dust fall.

Much further work is needed on the uptake of nutrients from successive horizons, and transfer from one horizon to another by leaching. Studies of root distributions indicate that in both forest and savanna at least three-quarters of the roots are in the top foot of soil. Root distribution is not a sure guide to feeding activity, but if the uptake from below the top foot is 20% of the total uptake, it is sufficient to account for the annual increase in nutrients stored in the vegetation.

## Chapter 4

## THE RESTORATION OF FERTILITY UNDER THE FALLOW

In this chapter we consider the beneficial changes that occur in the soil, particularly in the crop rooting zone, during the course of the fallow. These changes are closely linked with increases in the soil humus which helps to hold the exchangeable cations added to the topsoil in the nutrient cycle, stores important amounts of phosphorus and sulphur, and above all is the sole reservoir of nitrogen. The first section of this chapter is therefore devoted to soil organic matter and its influences. This provides a background for the second section in which the build up of total and exchangeable nutrients in the topsoil is considered. The nutrients accumulated in the topsoil, and in the vegetation itself, represent the total 'capital' gain during the fallow period.

Only the total increase in amounts of humus and nutrients in the topsoil and the vegetation during the fallow period is considered here. The availability to plants during a subsequent cropping period of the nutrients accumulated is obviously as important as the amount of increase. However, the availability of nutrients can be profoundly modified by the changes which occur in the soil when the vegetation is cleared and burnt. The availability of the nutrients will therefore be considered when the effects of clearing and burning are discussed in Chapter 5.

The development of favourable physical conditions in the topsoil under the fallow has been briefly described in the introductory chapter. Since this aspect of the restoration of fertility is best presented as a contrast to the conditions developed during the cropping period it will be discussed more fully in Part II.

## I. Soil Organic Matter

It is generally agreed that soil humus* increases in amount under the fallow. Unfortunately there are very few data available to show what the extent of the increase in humus is likely to be. Nevertheless, no quantitative appreciation of the changes in exchange capacity, nutrient availability, readily mineralizable organic nitrogen and phosphorus, etc., can be obtained unless some quantitative estimates of the changes of soil organic matter are available. In the first part of this section, therefore, methods for determining the increase in humus and nitrogen will be considered. In the succeeding parts the importance of the increases in relation to nitrogen, phosphorus and exchange capacity will be considered in more detail.

### (a) The increase of soil humus and nitrogen

The characteristic amounts of soil humus carbon and nitrogen, found in upper slope latosols are illustrated by the data collected in Table 7. Under moist lowland evergreen or semi-deciduous forest the maximum level that is attained after very long periods of fallow averages about 60,000 lb. per acre of C and 5,500 lb. per acre of N in the 0–12-in. layer. Higher levels on free-draining soils are attained (a) in highland areas, (b) in tropical lowland podzols, which may be developed on sandy materials under rainfall exceeding 120 in. p.a. (see Richards, 1952, for reproduction of a profile described by Hardon, 1937, and for a useful discussion of other occurrences) and (c) when the clay fraction contains allophane, as in many recent volcanic soils. Texture also accounts for some variation, clays tending to contain more organic matter than sands: for example Hardon (1936) found sands averaged 4% organic matter and clays 7% organic matter in the 0–4-in. layer under forests in southern Sumatra.

The levels attained after long periods under high-grass savanna are about 50,000 lb. C and 3,500 lb. N in the 0–12-in. layer. In drier regions, much lower levels may be found, 15,000 lb. C and 1,500 lb. N, or even less.

Cultivation reduces the amount of humus to an extent depending on the intensity of cultivation. For example, Reed (1951), as a result of large numbers of analyses of soils in Liberia, found the level of

* Since the term 'humus' has been reserved by many continental authors for some particularly 'active' fraction of the soil organic matter, we should explain that we use it to cover all soil organic matter that does not contain recognizable plant remains, as measured in a conventional wet combustion.

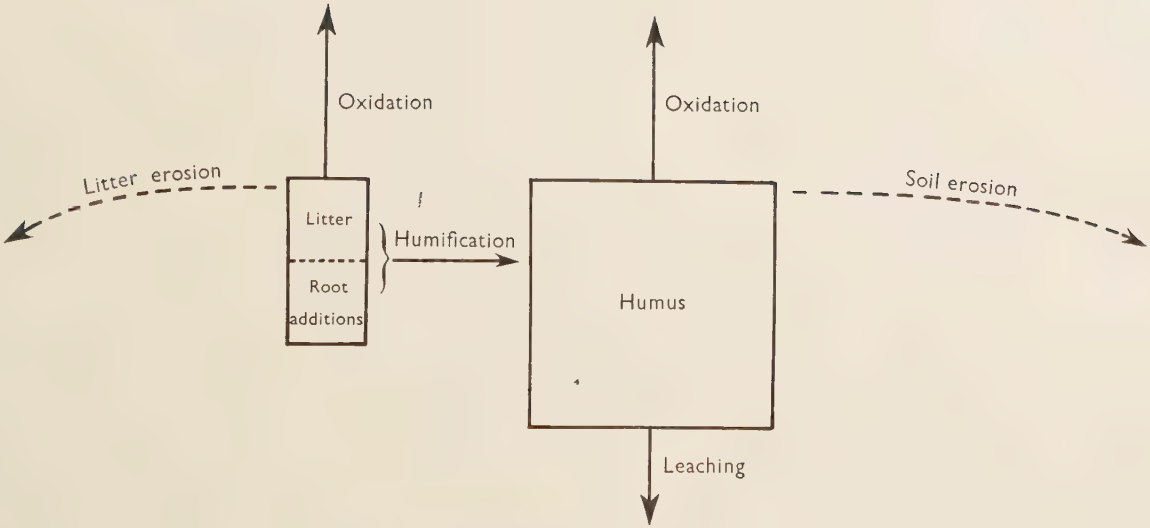


Fig. 2. Factors affecting the level of soil humus

organic matter under secondary forest was 75% of the level under virgin forest. The soils under secondary forest were cropped for 2 years and fallowed for about 10 years.

We have now to consider how rapidly the level of humus and nitrogen increases in a soil when it is left to rest after a period of cropping.

1. *Rate of Increase in Humus*

The rate of increase will depend primarily on the balance between the rates of addition of organic matter to the soil, and losses of organic matter from the soil. The processes involved are illustrated diagrammatically in fig. 2. The additions come from litter and dead root material; the losses by oxidation and, to a lesser extent, leaching. These processes in turn depend on a variety of factors, which will now be detailed.

(i) *Litter and root production*

The amount of fresh organic material produced will obviously depend on the type of vegetation established, and for a short-term fallow the initial rate of establishment and growth of the fallow will also be highly important. In the forest zone where the fallow regenerates from seedlings and stumps and roots left in the ground, and where rainfall is usually plentiful, rapid establishment will take place when the cropping period is complete. Bartholomew et al. (1954) found in the Congo that the leafy part of the vegetation was already as great after 5 years as after 18 years of fallow growth. In the savanna, water shortage at the end of the cropping period may prevent immediate regrowth, and the establishment of a complete cover can only occur during the subsequent wet season; even then only a weedy regrowth may appear and the establishment of a proper grass cover may take more than one season, particularly if the cropping period has been prolonged. Even when a grass cover has been established litter returns may be low, due to the destruction of the vegetation by annual burning. Prolonged cultivation in the forest zone may lead to the death of roots and stumps from which the woody vegetation would develop, and savanna grasses, self-maintained through fire, may supervene, causing not only a reduced rate of restoration of fertility but also a reduction in the maximum fertility level attainable. Waldock et al. (1951) report that in Sierra Leone land that has reverted to savanna requires a fallow period twice as long as land under developing forest.

Once the fallow is established the production of litter in the forest regions rapidly achieves a high level, of around 10,000 lb. per acre per annum (see Table 5). The simultaneous addition from dead roots, root slough and exudate is probably about half of this quantity. In the savanna zone the annual production of aerial parts of grasses depends greatly on the rainfall, as may be seen from

Table 2. If the high-grass Andropogoneae savanna is taken for illustration, 8,000 lb. of dry leaves and stems will be produced in a season, but very little of this will be added to the soil, most being lost as carbon dioxide during the annual grass burn. The addition from root material is probably only about one-third of this amount (for a discussion of the relationship of root-material additions to litter production see Greenland and Nye, 1959). Thus, while the production of organic material in forest regions is probably about 15,000 lb. per acre per annum, in moist savanna grassland areas only about 2,700 lb. becomes available to the soil organisms to increase the supply of humus in the soil.

*(ii) Losses of organic material*

Of the fresh organic material produced by the vegetation only a fraction will become incorporated with the soil humus, the remainder being lost through oxidation, and possibly also through leaching and erosion. The soil humus itself will also be subject to oxidation through the activities of soil micro-organisms, though its rate of destruction is very much less than that of fresh organic material. The proportion of fresh material converted to soil humus will probably lie between about 1/10 and 1/5 of the total, the actual proportion depending on a variety of factors, such as the composition of the material, lignin being much more resistant to oxidation than, for instance, sugars and polysaccharides; the extent to which the material decomposes on the soil surface or within the soil after burial by soil animals; and temperature and moisture conditions during decomposition. We know very little as yet about how these factors operate, and the nearest information about the proportions of litter retained as humus is obtained from the effects of mulches on soil humus. For a forest region of Ghana $7\frac{1}{2}$ tons of a grass mulch (70% dry matter) per annum increased humus carbon in the top foot of soil by 3,360 lb. per acre in 7 years (calculated from data of Stephens, unpublished). Assuming that the humus carbon was itself decomposing at a rate of 4% per annum during this period, this corresponds to a retention of slightly more than one-tenth of the carbon. For the savanna region of Ghana the same series of experiments indicated a retention of almost exactly 1/10 of the applied carbon. For the more woody material of forest litter, under a forest canopy, a rather higher retention may be expected.

For the root material, where the decomposition takes place entirely within the soil, a higher retention is again probable, but here even less information is available to provide a guide. The amount probably lies between $\frac{1}{5}$ and $\frac{1}{2}$ of the annual addition.

Thus in the forest zone, once the fallow is established, the annual addition to the humus carbon probably lies between $\frac{1}{2}(\frac{1}{10} \times 10{,}000 + \frac{1}{5} \times 5{,}000)$ and $\frac{1}{2}(\frac{1}{5} \times 10{,}000 + \frac{1}{2} \times 5{,}000)$, or 1,000 and 2,250 lb. of carbon per acre per annum. In this calculation half the air-dry litter and roots is assumed to be carbon. In the

high-grass savanna zone the corresponding additions will be much less, probably between $\frac{1}{2}(\frac{1}{5} \cdot 2{,}700)$ and $\frac{1}{2}(\frac{1}{2} \cdot 2{,}700)$, i.e. 270 and 675 lb. of humus carbon per acre per annum.

These figures do not represent the rate of increase of humus carbon under the fallow, as the humus is itself decomposing. This must of course be true as otherwise humus carbon would increase indefinitely. We know that at some stage equilibrium is reached when additions to humus carbon are equal to the losses, and there must therefore be a relationship between the level of humus carbon and the rate of decomposition. The simplest assumption to make, and the one that has been generally adopted, is that the rate of decomposition is directly proportional to the amount of humus carbon (see Jenny, 1941, and Chapter 6 in this account).

We may now estimate the rate of the increase of soil carbon under the fallow, once the additions have attained a constant rate.

We have

rate of increase = rate of addition — rate of loss,

or

$$I = A - k_f C \qquad (1)$$

where I is the annual increase of humus carbon in the soil
A is the annual addition of humus carbon
C is the present amount of humus carbon
$k_f$ is a decomposition constant.

This type of simple logarithmic increase is shown in fig. 3. The humus decomposition constant $k_f$ is calculated from a knowledge of the equilibrium level of humus in very long-fallowed soils in which the humus level has ceased to build up.

Here

$$A = k_f C_E \qquad (2)$$

where $C_E$ is the equilibrium level of humus carbon in the long-fallowed soil.

Using this method Greenland and Nye (1959) have calculated that for soils under tropical lowland-forest the decomposition constants for the 0–12-in. layer are between 2 and 5% per annum, and for soils under savanna are between 0·5 and 1·2% per annum.

It is very important to notice that the rate of increase of humus depends on how far removed the soil is from its equilibrium level. Thus, at any fraction p of the final equilibrium level an extremely simple relation gives the rate of gain of humus carbon. By substituting $pC_E$ for C in equation (1) we have

$$I = A - pk_f C_E$$

and by using equation (2) to eliminate $k_f C_E$ we have

$$I = A(1-p) \qquad (3)$$

Thus the rate of increase at 50% of the equilibrium level will be just twice that at 75% of the equilibrium level, provided of course that the production of humus carbon by the fallow remains the same. If, for the sake of illustration, we consider changes in the neighbourhood of the 75% level, as maintained in Liberia, equation (3) becomes

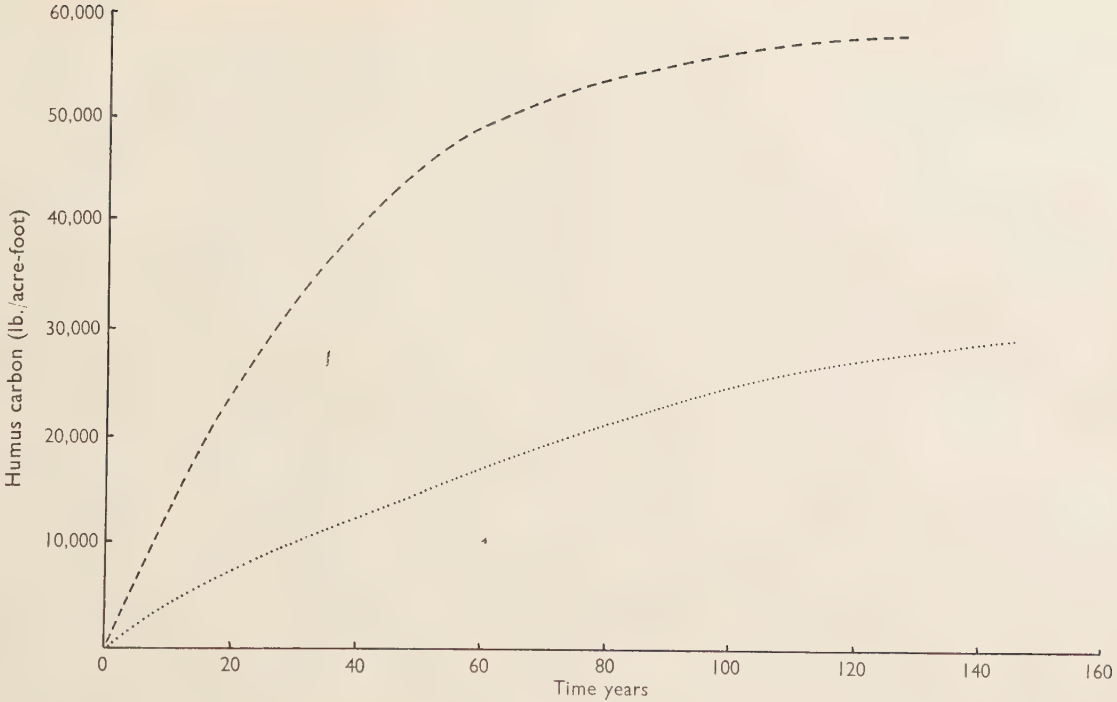


Fig. 3. Logarithmic increase in humus carbon calculated from the equation $t = \frac{1}{k} \ln \frac{A}{A-kC}$ where A is the annual carbon addition and k the decomposition constant.

---------- *Forest.* Annual addition of 1,800 lb. of humus carbon per acre and decomposition constant of 3% per annum ($C_E$=60,000 lb. per acre).

..... *Savanna.* Annual addition of 400 lb. of humus carbon per acre and decomposition constant of 1% per annum ($C_E$=40,000 lb. per acre).

$I = \frac{1}{4}A$, and the rate of increase of humus carbon lies between about 250 and 600 lb. per acre per annum in the forest zone, but is only between 70 and 170 lb. per acre per annum in the high-grass savanna zone, where the annual additions from the vegetation are much lower.

Another point needing emphasis is that the level of humus in a soil is not subject to large fluctuations with successive periods of fallow and crop. Even if the humus C increased near the 75% level at the higher rate of 600 lb. per annum, this is only 1 per cent of the average content in the top foot of soil under virgin forest—60,000 lb. per acre (Greenland and Nye, 1959). Thus on a soil at 70% of the maximum level a 10-year fallow would increase the carbon to 80% of the maximum level.

The calculation of the increase of soil humus by this method involves a number of assumptions, notably concerning the fractions of carbon in the organic-matter production incorporated with soil humus, the quantity of root organic matter produced, and the relationship between the rate of decomposition and the level of humus carbon. It is therefore highly desirable that it should have direct experimental verification. Unfortunately very few studies of differences in the organic-matter content of soils when under natural fallow and when cultivated have been reported. One obvious reason for this is that the differences will be relatively small, and unless the same soil is sampled at exactly the same depth and analysed in the same way at successive intervals over a period of several years, or very closely similar and well replicated sites are compared, then random differences are likely to outweigh differences due to the effects of the fallow. Most studies that have been reported show a failure to appreciate the importance of these points.

Another source of confusion in evaluating data on changes in soil humus is that little if any attention has been given to the importance of the equilibrium concept. According to this concept the effect of a fallow on soil organic matter depends as much on the initial organic-matter level of the soil in relation to the equilibrium level under the fallow as on the properties of the fallow itself. This makes it understandable why, for example, Joachim and Kandiah (1944) can report a large increase of organic matter under an elephant-grass fallow in the forest region of Ceylon (2,000 lb. per acre in 3 years), whereas in similar circumstances in the Congo, du Bois (1957) observed no addition to the soil organic matter from a similar fallow. Clearly the Congo soil must have been at or above its equilibrium level for grassland-fallow additions. Similarly Popenoe (1957) in Guatamala with a soil containing 18·0% carbon in the surface horizon found only insignificant organic-matter changes after forest fallows of 2 to 5 years. It is therefore evident that the effects of a fallow in increasing soil organic matter can only be judged in relation to the maximum level that can be attained beneath it.

The best evidence in support of the equilibrium concept is to be found in observations on very young fertile soils, such as the

volcanic-ash deposits at St. Vincent studied by Hardy (1939). Here he observed an increase of organic matter in the top 6 in. of soil, under rapidly developing forest vegetation, of 34,000 lb. per acre in a 17-year period. Such a high rate is only to be expected in a soil a long way below its equilibrium level. The rapid increase of organic matter on eroded land planted to legumes, and therefore a rather particular case, observed by Smith, Samuels and Cernuda (1951) in Puerto Rico is also only to be expected in soil where the organic-matter level is much below the maximum. Further evidence that satisfactory restoration of soil humus is effected by a forest fallow is provided by the relatively high levels of humus found in soils which have been under many cycles of cultivation and fallow (see references on p. 104).

2. *Rate of Increase in Nitrogen*

If we know the rate of increase of humus C in the soil during a fallow, and also the C/N ratio, we can easily calculate the increase in soil N. On a given soil the C/N ratio may rise slightly during the fallow period and fall slightly during the cropping period, but for the present purpose the effective gain in N parallels the gain in C. Sound evidence for this is provided by Reed's (1951) data for Liberia where the C/N ratio for cropped land is 17·1, for forest fallow is 16·3, and for virgin forest is 18·0. Similarly Jenny et al. (1948) found no systematic difference between the C/N ratio of soils under crop, under secondary forest and under virgin forest, in Colombia. For the high-grass-savanna zone Anthony and Willimott (1956), in a well replicated trial, found insignificant differences between plots fallowed for 6 years and those cropped for the same period.

At 75% of the equilibrium level of soil organic matter the average rate of increase of soil nitrogen in the forest zone will be c. 35 lb. per acre and in the high-grass-savanna zone c. 10 lb. per acre, assuming for both a constant C/N ratio of 12. Thus a 10-year fallow period will lead to accumulation of about 350 and 100 lb. of nitrogen under each fallow. These amounts do not of course represent the total nitrogen gain of the soil-fallow system during the fallow period. A 10-year-old forest fallow contains roughly 600 lb. of nitrogen, and the nitrogen lost in the grass burn in the high-grass savanna will be around 25 lb. annually. The respective net annual fixation rates in forest and savanna must therefore be of the order of 95 and 35 lb. per acre. However, because all nitrogen stored in the fallow is lost in the burn on clearing it is only the soil increment that can be used by crops in the succeeding cropping period.

(b) The source of the nitrogen increment

The estimates of the net annual fixation rates given above do not represent the total fixation that may be occurring under the fallows, as some nitrogen may be lost by leaching and denitrification, at least in the moist semi-deciduous-forest areas where levels of the nitrate

ion in the soil solution may be high. Even in these areas, however, leaching losses are unlikely to be very great as nitrate ions which might be lost under a shallow-rooted crop are likely to be intercepted by the more developed root system of a perennial cover. Nevertheless a rate of increase of 100 lb. per acre per annum, equivalent to 5 cwt. of sulphate of ammonia, is a considerable amount for which to have to account.

The small increment from rainfall, about 7 lb. per acre per annum, has already been mentioned (p. 45). Subsoil supplies, which are important for other nutrients, can be discounted here, as the only sources in the subsoil are fixed ammonium, and nitrogen in old dead roots, which is unlikely to be mineralized unless it is brought to the surface by the action of soil fauna. The principal source for the nitrogen increment must therefore be the atmosphere, the fixation of atmospheric nitrogen being carried out by micro-organisms—either free-living or associated symbiotically with legumes or possibly other species.

Jenny (1950) suggested that the probable reason for the high levels of nitrogen in the highly leached forest soils of Colombia was the large number of legumes, estimated at over 50%, among the forest trees. In the rain forests of British Guiana, Davis and Richards (1934) found a high proportion (over 50%) of leguminous trees on a heavily leached acid soil, but a very much smaller proportion on less acid soils of the red-earth group. Similarly, in the forests of Nigeria the rain forest contains many legumes, but not the drier forest areas (Keay, 1953). Beirnaert (1940) estimates that in the forests of the Central Congo Basin, under an intermediate rainfall of about 70 in. per annum, the proportion of legumes is 25%, and that they may contribute about half of the annual nitrogen increment which he estimates as 90 lb. per acre. Smith et al. (1951) found only 3% of legumes in the drier forest areas of Puerto Rico, and dismissed them as an unimportant source of nitrogen gain. Thus the nitrogen increment from symbiotic fixation in leguminous species may be important in the heavily leached acid soils of the rain-forest areas, although there is little evidence available at present to show whether or not symbiotic fixation does occur with such species. Bonnier (1957) found that only about half the leguminous species in the Yangambi forest bore root nodules. In the drier forest areas it is very unlikely that symbiotic fixation makes any important contribution, though it may do so if leguminous species are common in the early stages of regrowth on cultivated sites. There are no available data on this point, as the figures quoted refer to established forest.

In the savanna zone leguminous trees and shrubs are frequent, but it is doubtful if they support nitrogen-fixing bacteria, or if they do, that the organisms are active in nitrogen fixation. Thus Nye (1958) has shown in high-grass savanna soils very low in nitrate that nitrogen content is low for leguminous species generally, and recent

work in Australia (Hannon, 1949, quoted by Norris, 1956) indicates that the growth of Rhizobia with these species may be severely restricted by periods of water shortage. It is possible that a contribution may be derived from organisms living in symbiosis with species other than legumes (Van Faber, 1912; Bremekamp, 1933; Aubreville, 1950) since nitrogen-fixing bacteria have been found in root and leaf nodules of a number of non-leguminous savanna trees, but little is known at present about such symbiotic fixation.

It therefore appears that non-symbiotic nitrogen fixation must be the most important contributor to the nitrogen increment in the moist semi-deciduous-forest zone, and that it may make a notable contribution in the higher- and lower-rainfall regions also. Of the organisms likely to carry out the fixation, *Azotobacter* spp. occur in the neutral ochrosols of the forest zone and the less acid savanna soils, and *Beijerinckia* spp., which include the former *Azotobacter indicum* (Altson, 1936; Starkey and De, 1939; Derx, 1950) and *Azotobacter lacticogenes* (Dommergues, 1953c) are known to be widespread in the tropics (Kauffmann and Toussaint, 1952; Boquel, Kauffmann and Toussaint, 1953; Tchan, 1953a & b; Dommergues, 1953b; Meiklejohn, 1954; Ruinen, 1956). *Clostridia* spp. are also widely distributed. Considerable attention has been given to the importance of nitrogen-fixing blue-green algae in swamp-rice soils. It is possible that they are important in forest soils also, but very little is known at present about their distribution.

It is perhaps not surprising that a high rate of nitrogen fixation should occur in the forest areas, as not only are temperature and moisture conditions highly suited to microbial activity, but there is a very high rate of production of carbonaceous material to provide the necessary energy for nitrogen fixation. In this connection it is perhaps significant that in both the moist semi-deciduous-forest and the moist evergreen-forest zone also, fertilizer experiments indicate that plant growth is not limited by nitrogen deficiency. A productive cycle is thus created in which the active growth of the forest ensures a sufficient supply of energy material for nitrogen fixation to support the continued growth of the forest. In the savanna zone dominated by the Andropogoneae, repression of nitrogen mineralization implies that the vegetation, except for certain legumes, is short of nitrogen. Hence development is restricted and much less carbonaceous material is available for any nitrogen-fixing organisms present in the soil.

### (c) The increase in organic phosphorus

The ratio of organic phosphorus to carbon in the generally phosphorus-deficient soils of Ghana is about 1 : 200 (Nye and Bertheux, 1957), and a similar ratio is found in similarly deficient tropical soils elsewhere (Bouyer, 1958). Thus the increase under a 10-year fallow in forest areas at the 75% equilibrium level will be of

the order of 12–30 lb. per acre. In the high-grass savanna the corresponding increase will be between 3 and 9 lb. The amounts of organic phosphorus accumulated in the soil organic matter during a 10-year forest fallow may be compared with the amount of 30–40 lb. accumulated in the vegetation. In savanna, the P stored in the grass of a high-grass fallow is about 10 lb. per acre. Thus it appears that the increase in organic phosphorus in the soil is a useful function of the fallow. There is no direct evidence to show whether this organic phosphorus is mineralized at the same rate as organic nitrogen, but it is reasonable to assume that this is so (see Black, 1957, p. 266).

(d) The increase of cation-exchange capacity

The exchange capacity of the surface horizons of the kaolinitic soils we are considering depends largely on their organic-matter content. In neutral and slightly acid top soils such as occur in the moist semi-deciduous and savanna regions, the storage of cations in the exchangeable pool may be limited by the level of the exchange capacity. Furthermore, when the fallow is cleared, the large quantities of cations released from the vegetation will raise the percentage saturation and pH in the soil to a level which depends on the exchange capacity (see chapter 5). The higher the pH the greater will be the production of nitrate, and also the concentration of bicarbonate ion, which becomes appreciable above a pH of 6·0. Since these anions are balanced by cations the rate of leaching of cations will be correspondingly increased.

There is no reliable direct measure of the rate of increase in exchange capacity under fallows. A useful indication may, nevertheless, be obtained by combining a figure for the exchange capacity for soil organic matter with the organic-matter increases derived above. The exchange capacity of the organic matter in a range of forest ochrosols and oxysols in Ghana is about 350 m.e. per 100 g. C, when determined by leaching with normal ammonium acetate (de Endredy, 1954 and priv. comm.). We have shown that an average increase of organic C in a 10-year fallow period near the 75% level in the forest zone will be about 4,000 lb. The corresponding increase in exchange capacity will be about 14 lb. equivalents. This would mean an increase in calcium adsorption capacity of 280 lb. per acre, an appreciable amount.

In the savanna zone the increase of organic carbon in 10 years may be about 1,200 lb. per acre. On the same basis as above this would increase the exchange capacity by about 4·2 lb. equivalents per acre, which could increase calcium storage by about 84 lb. per acre.

(e) The quality of the humus addition

We have so far considered only the increases in the total amount of humus and organic nitrogen and phosphorus, and exchange capacity. It is however believed by many that measurement of the

total soil carbon does not give a measure of the "humus" in the soil—that there is some fraction of the total organic matter present that is particularly involved in soil fertility, whereas the remainder is inert and relatively valueless. Various methods have been suggested for measuring the "active" humus, and in fact have been widely used by many European workers. Thus it has been claimed that ploughing-under a single crop of green millet at Sefa, Senegal, raised the 'humus" content by 50% (Fauck, 1954). The value to be attached to such measurements is by no means certain. In assessing their value it is first of all essential to be quite clear about what is meant by humus quality. Good-quality humus has at the least the following properties: (1) it breaks down readily to yield the plant available forms of mineral nitrogen, sulphur and phosphorus, but does not decompose so rapidly that excessive losses of humus or of nutrients occur; (2) it has a high cation-exchange capacity; (3) it improves the constitution of the soil, thereby improving its water relationships and the diffusibility of carbon dioxide and oxygen through the soil; (4) it provides food for the soil micro-organisms, particularly the nitrogen-fixers.

The quality of humus has been assessed by chemical extraction, and by its C/N ratio.

### 1. *Extraction Methods*

The organic matter in the soil is a very complex mixture of organic compounds, so intimately associated with the inorganic soil colloids that no one has yet succeeded in making a complete separation of the organic and inorganic components. Undoubtedly not all the organic compounds present in the mixture are equally important in conferring the properties associated with good-quality humus on the soil, but no fractions have yet been extracted which have been shown to be correlated with the desirable properties mentioned above.

Nevertheless various extraction methods supposed to separate 'active' humus have been used. The methods at present most in favour are the ammonium-oxalate extraction method of Chaminade (1946) and the sodium-fluoride and acid-precipitation method of Laudelout and d'Hoore (1949).

It is difficult to make any critical assessment of Chaminade's method as no satisfactory data have been presented to show whether or not the organic fraction extracted correlates with the properties of good-quality humus. Ammonium oxalate was originally selected by Chaminade as the extracting reagent on the grounds that of the various weakly alkaline salts tested as extractors of 'humus' it removed the most. Fauck (1956) after analysing "plusieurs milliers" samples from French West Africa by the method states "Mais il faut noter que le taux d'humus n'a pas pu être mis en corrélation significative avec les rendements ou avec le carbone que ce soit

## TABLE 7

**Carbon and Nitrogen Contents, pH and C/N Ratios for Surface Samples of Free-draining, Upper-slope Soils of Different Lowland Ecological Zones**

| Area | Rainfall (in. p.a.) | No. samples | Depth in. | pH | C% | N% | C/N | Reference | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| **1. Moist, evergreen forest zone (Forest Oxysols)** | | | | | | | | | |
| Colombia | 150–330 | 13 | 0–8 | 4·9 | 3·90 | 0·31 | 12·6 | Jenny, 1948 | |
| Southern Sumatra | c.90 | 971 | 0–4 | 4·0–7·6 | 3·60* | 0·29 | 12·4 | Hardon, 1936 | Virgin and old secondary forest |
| Malaya | c.100 | 7 | 0–3 | 4·2 | 4·0 | 0·25 | 16·1 | Coulter, 1950 | Virgin jungle |
| Liberia | 80–180 | 47 (0–3) 14 (3–6) | 0–6 | 4·3 | 2·50 | 0·14 | 17·9 | Reed, 1951 | Virgin forest |
| South-west Ghana | 70–85 | 22 | 0–6·5 | 4·4 | 2·20 | 0·18 | 11·7 | Ahn, 1958 | May include cultivated land |
| South-west Ghana | 70 | 1 | 0–6 | 4·2 | 4·10 | 0·33 | 13·5 | Charter, 1955 | Representative oxysol under old secondary forest |
| Southern Nigeria | 80–90 | 20 | 0–4 | 4·4 | 1·35 | 0·083 | 16·2 | Vine, 1953 & 1956 | Secondary forest and oil palm groves |
| Madagascar | 80 | 15 | 0–6 | 5·6 | 1·82* | 0·12 | 15·2 | Pernet, 1954 | Forêt dense humide (Littorale) |
| Ivory Coast | 60–80 | 5 | 0–4 | 4·2 | 1·40* | 0·098 | 14·3 | Berlier et al., 1956 | |
| **2. Moist semi-deciduous forest zone (Forest Ochrosols)** | | | | | | | | | |
| Ghana | 50–70 | 23 | 0–9 | 6·3 | 1·80 | 0·19 | 9·5 | Charter, 1955 | Virgin and old secondary forest |
| Nigeria | 50–70 | 7 | 0–4·5 | 6·5 | 1·85 | 0·17 | 10·9 | Vine, 1953 | Old secondary forest |
| Trinidad | 70 | 16 | 0–6 | 6·2 | 1·00 | 0·13 | 7·7 | Hardy and Evans, 1945 | Samples taken in opening young secondary forest |
| Ivory Coast | 60 | 3 | 0–4 | 6·6 | 2·90* | 0·30 | 9·6 | Leneuf, 1956 | |
| Colombia | 47–59 | 8 | 0–8 | 6·3 | 1·49 | 0·14 | 10·6 | Jenny, 1948 | "Under forest or brush" |
| Madagascar | 43 | 8 | 0–4 | 6·5 | 1·57* | 0·13 | 12·1 | Pernet, 1954 | "Forêt ombrophile" |
| **3. Savanna zone** | | | | | | | | | |
| Ghana | 50–60 | 11 | 0–6 | c.6·0 | 0·59 | 0·041 | 14·5 | Nye, 1950 | "Long rest" sites—Andropogoneae |
| Ivory Coast | 60–80 | 5 | 0–4 | 4·6 | 1·15* | 0·063 | 17·5 | Berlier et al., 1956 | *Hyparrhenia* and *Loudetia* spp. |
| Nigeria | 40–50 | 3 | 0–5 | 6·6 | 1·36 | 0·079 | 17·3 | Vine, 1956 | Savanna woodland—Andropogoneae |
| N. Rhodesia | 40–55 | 7 | 0–4 | 5·9 | 0·99 | 0·055 | 18·0 | Ballantyne, 1958 | Savanna woodland, including cultivated land |
| Ghana | c.45 | 9 | 0–6 | c.6·0 | 0·44 | 0·034 | 12·9 | Nye, 1950 | "Short fallow" sites—Andropogoneae |
| Madagascar | 43 | 14 | 0–4 | 6·9 | 0·89* | 0·083 | 10·7 | Pernet, 1954 | Andropogoneae (*Heteropogon* & *Cenchrus* sp.) |
| Ghana | c.40 | 6 | 0–6 | c.6·5 | 0·34 | 0·035 | 10·0 | Nye, 1950 | Almost continuously cropped |
| Tanganyika | 34 | 11 | 0–6 | 6·3 | 1·04 | 0·061 | 17·0 | Anderson, 1957 | Miombo savanna woodland |
| N. Rhodesia | 25–34 | 8 | 0–3 | 6·4 | 1·04 | 0·073 | 14·2 | Ballantyne, 1958 | |
| N. Nigeria | 28–32 | 4 | 0–6·5 | 6·2 | 0·23 | 0·022 | 10·5 | Vine, 1956 | Includes farmland |
| Upper Niger | c.15 | 10 | 0–6 | 5·6–6·9 | 0·29* | 0·023 | 12·6 | Dabin, 1953 | "Virgin" soils |

* Not apparent from original whether recovery factor applied. All other carbon data based on dichromate oxidation determination, corrected by a recovery factor.

après engrais vert, après jachère, après arachide, après céréales, ou sous forêt".

Laudelout and d'Hoore investigated the relation between their "matière humique précipitable" (MHP) and the microbiological population of a wide variety of soils in the Belgian Congo. They found interesting differences, but their own conclusion was that "il existe de trop nombreuses divergences pour que la détermination de cette fraction de la matière humique fournisse dans tous les cas une indication exacte sur le niveau ou la nature de l'activité de l'ensemble de la microflore saprophytique . . . Lorsque cette méthode est appliquée à des types de sol différents sous divers couverts végétaux, elle semble soulever beaucoup plus de problèmes qu'elle n'en resout". Thus this approach can be of little general use unless many more critical studies of its application are made.

Bremner (1954) in reviewing methods of investigating soil organic matter states "it is now generally realized, however, that such (non-isolative) methods are of very limited and uncertain value". Laudelout and d'Hoore's findings would seem to bear this out. Bremner suggests that much more attention should be given to the isolation of identifiable chemical compounds from soil humus. This approach has not yet been developed to any extent. Until it is, and until specific organic compounds or groups of compounds are shown to correlate closely with the desirable properties of good-quality humus, we shall have to be content with measurements of organic carbon as measurements of 'humus' carbon. Fortunately, most of the properties associated with good-quality humus can of course be measured directly, and will be discussed in more detail in Part II.

### 2. *The Carbon/nitrogen Ratio of the Humus*

Before leaving the question of the quality of soil humus there is one further and often quoted measure to be considered, namely, the C/N ratio. It can be seen from Table 7 that the C/N ratio is a characteristic of the major soil groups we have been considering. In the forest ochrosols in which bacterial activity is high it has a value of 8–12, similar to that of temperate regions. In the acid oxysols under forest the C/N ratios are higher—14–17. Figs. 4 and 5, taken from Hardon (1936), show clearly the relationship between pH and organic carbon and pH and C/N ratio, for almost one thousand samples of the 0–4-in. layer beneath old secondary or virgin forest in the lowland areas of Sumatra.

In the neutral or slightly acid ochrosols under long-established high-grass (Andropogoneae) savanna the C/N ratio is again high (15–20). In long-cropped savanna soils, or under elephant grass, or under tall bunch grass the limited evidence is that the ratio is less.

The view is often expressed that humus of high C/N ratio is only slowly mineralized, whereas humus of low C/N ratio mineralizes readily. There is ample evidence, discussed in Chapter 6, to show

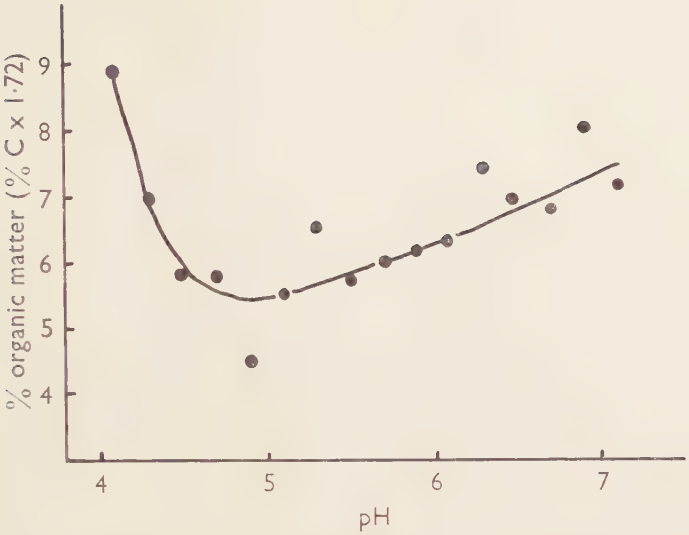


Fig. 4. Relation between pH and organic-matter content for 971 soil samples (0-4 in.) from southern Sumatra (Hardon 1936).

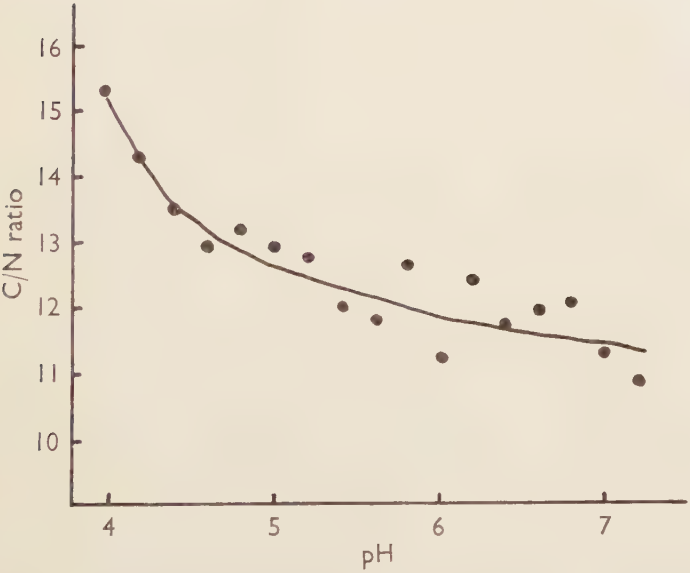


Fig. 5. Relation between pH and C/N ratio for 971 soil samples (0-4 in.) from southern Sumatra (Hardon 1936).

that the humus of the typical ochrosols does in fact mineralize rapidly under forest. As regards the humus of high C/N in the oxysols, there are little data to indicate the rate of mineralization under forest. If it is in fact less than in the ochrosols we would expect levels of humus in these soils to be greater. Hardon's data in figs. 4 and 5 do in fact show that at pH of less than 4·5 both organic-matter content and C/N ratio begin to increase rapidly. No doubt this trend links with the accumulation of humus of high C/N ratio found under the extreme conditions of a tropical lowland podzol. From the data given in Table 7 however, the levels of humus in oxysols are not always greater than in ochrosols. There is little reason for believing that in most oxysols the high C/N ratios are necessarily correlated with low mineralization rates. The general level of microbiological activity is, however, certainly much lower than in the ochrosols (Laudelout and du Bois, 1951; Dommergues, 1956), but while the population of nitrifying bacteria is extremely low the numbers of ammonifiers are high (Dommergues, 1952a). When the forest oxysols are cropped nitrification becomes rapid (see Chapter 6); thus their high C/N ratio is no guide to their ability to supply crops with available nitrogen.

The humus of very high C/N ratio found in the high-grass (Andropogoneae) savanna zone has been calculated to mineralize under the natural vegetation at a rate of only 0·5–1·2% per annum (Greenland and Nye, 1959), and this low rate of mineralization is known to persist at least to some extent after the natural vegetation is cleared and the land cultivated (p. 109). We know little concerning the rate of mineralization under other types of well established savanna vegetation, but on cultivation of soils in these areas mineralization is rapid.

It thus appears that the C/N ratio is at least a rough guide to the rate of mineralization of the humus. It will however be of little general use until we know much more concerning the relationship between the C/N ratio and the other desirable properties of humus.

## II. The Build-up of Total and Exchangeable Nutrients in the Topsoil

### (a) Total nutrients

In forest, during the fallow period more nutrients are accumulated in the standing vegetation than in the top soil and the rate of accumulation of nutrients in this form has already been described. There is, however, in addition a significant net transfer of some nutrients from the subsoil to the topsoil during a period under fallow, tending to make good net losses from the top soil that occurred during the previous cropping period.

There have been no direct measurements of changes occurring within the soil during a fallow period, and in the absence of any knowledge of the amounts of nutrients leached from the different soil horizons, and of any precise knowledge of the proportions

taken up from surface and subsurface horizons it is not possible to estimate the probable magnitude of such changes.

One can, however, draw some general conclusions about the increases occurring in the all-important topsoil from the analyses of soils under long-established fallows. It has been mentioned on p. 43 that soils under forest contain more total phosphorus and calcium in the surface horizon (0 to 2–4 in.) and to a lesser extent in the immediate subsurface horizon than in lower horizons. Though this is well known, it is by no means self-evident that it should be so. Especially on the highly leached soils it might be expected that the high proportion of elements stored in the forest vegetation itself, and the concentration of feeding roots in the topsoil, would lead to a zone of depletion there. That this does not occur indicates that the nutrients brought up from the subsoil over centuries and returned through the litter to the feeding zones of the topsoil are sufficient to compensate for leaching losses and the loss to the standing vegetation. Further evidence on this point is provided from the wattle plantations of Natal established on leached lateritic soils. Orchard and Darby (1956*b*) have shown that the top soil (0–9 in.) containing 516 lb. exchangeable Ca and 374 lb. exchangeable K has not altered appreciably during three 10-year cycles of wattle during which 900 lb. of Ca and 600 lb. of K were exported as bark and timber.

For savanna soils the accumulation of total P in the surface is less marked (Nye and Bertheux, 1957). No data for other nutrients are available.

We shall return to the question of the total nutrient reserves in the soil in chapter 7, where the long-term effects of removal of nutrients in crops on the soil's capacity for sustained production will be considered.

### (b) Exchangeable nutrients

It will generally be true that after a sufficiently long period of rest the exchangeable nutrients in the topsoil will be restored nearly to their original levels, provided the soil has not been devastated by erosion during the previous period of cropping, or savanna has not become established on forest soils. The reasons for this are firstly that the humus largely responsible for holding the cations will be restored to its former level, and secondly that the addition of cations to the surface in the form of litter and rain-wash will be the same if the fallow is in the same condition as in the previous cycle. There are no direct measurements on the changes in exchangeable cations taking place in the topsoil during the fallow. Such measurements are no simple matter to obtain for the same reasons that reliable data for increases in organic matter are not available. Estimates have therefore to be made by indirect methods.

The change in the exchangeable nutrients in the top soil during the fallow period will be the result of the balance between:

1. addition of subsoil nutrients through litter fall and rain-wash (only a fraction of the total nutrients in the litter will be derived from the subsoil);
2. loss by uptake from the top soil by the fallow, and leaching to the subsoil.

There are too many uncertainties in this balance to enable us to predict even approximately the changes in the top soil. However, calculations using data from the Yangambi fallows and 'likely values' for the extent of subsoil feeding indicate that in the early stages of a fallow when increase of storage is rapid compared to litter fall, there may be a net loss from the top soil. Later when litter fall greatly exceeds increase in storage the amount of nutrients in the topsoil may be restored and increased.

Another approach depends on the fact that the increase in exchangeable cations during the fallow will be related to the increase in exchange capacity due to the increase in organic matter, as already described, and on any change in the proportion of the cations in the exchange complex.

The rather scanty evidence available does not indicate any marked change in the pH or the percentage saturation in the top soil during the fallow period. For example, calculations from Reed's (1951) analyses of Liberian forest soils yield the following figures:

| | | | % Saturation | | |
|---|---|---|---|---|---|
| | | pH | K | Ca | Mg |
| Soils under secondary forest | 0–9 in. | 4·16 | 4·9 | 10·0 | 5·6 |
| Soils under virgin forest | 0–9 in. | 4·17 | 4·5 | 10·1 | 5·6 |

and in Anthony and Willimott's (1956) studies land under high-grass savanna had a pH of 6·7 compared with land cropped for 6 years with a pH of 6·5.

We have estimated that the cation-exchange capacity may increase by about 14 lb. equivalents in forest and by 4·2 lb. equivalents in high-grass savanna during a ten-year fallow at 75% of equilibrium. If the cation-saturation percentage does not change the increased storage of cations may be calculated for representative cases. In the unsaturated forest oxysols of Liberia, containing 5% K, 10% Ca and 6% Mg by equivalents in the exchange complex the increases in the top foot will be 28 lb. K, 28 lb. Ca and 10 lb. Mg. These amounts are only about one-twentieth of the accumulation to be expected in the fallow itself. The increases of exchangeable cations may be more important if the soil is well below the equilibrium level so that the increase in exchange capacity is more rapid; and if the exchangeable cations occur in greater proportion in the exchange complex, as in the forest ochrosols.

In savanna soils in which the amount of nutrients stored in the vegetation is so much lower than in forest soils, the increase in the soil itself during the fallow period assumes greater importance.

With 10% K, 50% Ca, 20% Mg in the exchange complex the increase over a 10-year period is 17 lb. K, 42 lb. Ca, 10 lb. Mg. per acre. This may be compared with 51 lb. K, 33 lb. Ca and 28 lb. Mg stored in a high-grass fallow.

We may now summarize the forms in which the increase in the supply of nutrients during a fallow period is expressed. Many of the estimates made in this chapter are approximate. Nevertheless they indicate the order of magnitude of the effects considered, and help to sift the significant from the insignificant.

Accumulation of nutrients occurs both in the vegetation and in the top soil. The increase in the latter is largely associated with the increase of humus. The rate of increase depends on the maximum level of humus that can be attained under the fallow, and how far the soil falls short of this level—thus once a fallow is established, humus increases more rapidly the further the soil is from equilibrium. The level maintained when there is no great pressure of population is probably around 75% of the maximum level.

Since nitrogen is lost when the vegetation is burned, the increase of organic nitrogen in the top soil is all important. The C/N ratio changes little during the fallow, and the increase in N parallels the increase in humus. At the 75% level the annual increase in nitrogen under forest fallow is around 35 lb. in the soil and 60 lb. in the vegetation; while in savanna it is 10 lb. in the soil, and a further 25 lb. is lost by grass burning. These amounts seem to be derived largely from non-symbiotic fixation.

The increase of organic phosphorus in the humus under a forest fallow is comparable with the amount accumulated in the vegetation over a ten-year period. The corresponding increase in the soil under high-grass savanna is smaller, but so too is the amount stored in the grass.

Increases of exchangeable potassium, calcium and magnesium are in general small compared with the amounts of these elements accumulated in a forest fallow. Increases in the exchangeable form, particularly of calcium, are likely to be more significant in savanna fallows.

Other functions of the fallow such as the suppression of pests, diseases and weeds, and the improvement of the physical constitution of the soil and its protection from erosion, are discussed in Part II in the form of a contrast to the conditions prevailing during the cropping period.

# PART II—THE CROPPING PERIOD

## Chapter 5

## THE EFFECT OF CLEARING AND BURNING

The analysis of the cropping period falls naturally into two sections: the sudden changes in the soil that occur when the fallow is cleared and burned—to be considered in this chapter; and the slower changes in the physical, chemical and biological properties of the soil that lead to the decline in its fertility during cropping—these are treated in the next chapter.

In the forest zone clearing in preparation for planting takes place during the dry season. It is usual to cut and burn all the underbrush and small and medium sized trees, but some of the larger trees may be left standing; these cast a light, patchy shade over the crops, and assist reseeding of the fallow. Other things being equal, a mature secondary forest which is easy to cut and burn is selected. Virgin forest may give more sustained yields and require less weeding, but it is difficult to cut and takes longer to dry. Conklin (1957), who gives in detail the labour requirements for each farming operation among the Hanunoo in the Philippines, estimates that clearing and burning virgin forest requires 605 man-hours per hectare, while mature secondary forest, about 20 years old, requires 395 man-hours per hectare. In addition primary forest areas are more exposed to animal pests such as monkeys and rodents, and guarding activities are reckoned to take 550 man-hours per hectare as against 275 man-hours per hectare in plots cleared from secondary forest. Virgin forest may, however, be cleared because this gives rights over land, and also provides timber for building and logs for dugout canoes, as described, for example, by Freeman (1955) in Sarawak. In the savanna the grasses are fired during the dry season and excess woody vegetation is cut and burned. Certain trees valued for their produce, e.g. shea butter, *Butyrospermum parkii*, or for their light shade, e.g. *Daniellia oliveri*, are preserved; and if yams are to be planted, the live tree stems up which the vines can be trained are also preserved.

In both forest and savanna, burning is essential. In forest, it is only by burning that the ground can be cleared of the great mass of felled vegetation, and made accessible for planting food crops. All plants in the herb layer are killed by the burn, and the ground is left

perfectly clean for the farmer to plant the first crop. All the nutrient elements in the fallow except nitrogen and sulphur are preserved and added to the soil in the ash. The loss of organic carbon and nitrogen that is entailed is often deplored, but it is unavoidable. There is no practicable way of incorporating this material in the soil to form stable humus. In grassland, burning is equally essential: a farmer's primary object is to prevent regrowth of the grass by the simplest means, and it is quite impracticable to bury grassland vegetation with a hand hoe.

The effects of the burn are threefold:

(i) Large quantities of nutrient ions from the standing vegetation and the litter layer are spread in the ash on the surface of the soil in the form of carbonates, phosphates, and silicates of the cations. Nearly all the nitrogen is, however, lost to the atmosphere as ammonia, gaseous nitrogen or the oxides of nitrogen, and sulphur as sulphur dioxide.

(ii) The immediate soil surface is heated, and this has some direct effect on the microbiological population, on the physical and chemical properties of the soil colloids, and on the availability of nutrient ions.

(iii) The change in pH and nutrient availability may cause a very different microflora from that originally present to develop.

We shall consider first the net quantity of nutrient elements that are added to the soil in the ashes, and then the secondary effects which follow from the addition of ash—the increase in pH and the heating to which the soil is subjected during the burn.

### (a) Addition of Nutrients

It is possible to estimate the amounts of nutrients added to the soil when the fallow is burnt either from a knowledge of the nutrients stored in the fallow, making allowance for unburned stumps, roots and large trees; or by analysing soils before and after clearing. There are, however, only a few investigations in which sufficient attention has been paid to sampling errors to make the latter method worthwhile. Estimates obtained by both methods are presented in Table 8. The magnitude of the increase may be expected to be related to the age of the forest destroyed, though because increase in nutrient storage in old forest takes place predominantly in woody material, (chapter 2) and much of this may not be readily combustible, it will not be directly proportional to the age of the forest. The thoroughness with which the burn is carried out will also determine to some extent the quantities of nutrients added to the soil. The data from Kade, Ghana, for the effects of burning 40-year-old forest show the largest increases. It is seen that the nutrients added agree well with those contained in the combustible parts of the vegetation, (example 1, Table 2). These data were obtained by taking composite soil samples, each of 50 cores, from a set of 8 plots each of 1/25 acre, before the forest was disturbed and immediately after clearing and

## TABLE 8

### Soil Changes following the Clearing of Fallows

| No. | Place | Rainfall in. p.a. | Depth in. | pH | C% | N% | Av. P p.p.m. | K meq. | Ca meq. | Mg per 100 g. | TEC | CEC | Total Added (lb. per acre) N | P | K | Ca | Mg | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Kade, Ghana | c.65 | 0–2 | 5·21 | 2·22 | 0·210 | 9·8 | 0·41 | 5·7 | 1·21 | | 10·1 | | | | | | Mean of 8 plots under 40 year old forest. |
| | | | 2–6 | 4·73 | 1·11 | 0·110 | 3·6 | 0·33 | 3·6 | 0·95 | | 7·0 | | | | | | |
| | | | 6–12 | 4·63 | 0·87 | 0·089 | 1·9 | 0·32 | 3·0 | 0·94 | | 6·7 | | | | | | |
| | | | 0–2 | 7·9 | 2·26 | 0·198 | 30·0 | 2·01 | 17·9 | 2·7 | | 9·9 | —100 | 23 | 670 | 1410 | 170 | |
| | | | 2–6 | 6·4 | 1·26 | 0·117 | 8·0 | 0·81 | 4·6 | 1·3 | | 5·7 | | | | | | Mean of same 8 plots immediately after clearing and burning. No cultivation. |
| | | | 6–12 | 5·7 | 0·94 | 0·081 | 5·0 | 0·42 | 3·0 | 1·1 | | 6·4 | | | | | | |
| 2 | Belgian Congo | c.75 | 0–4 | 4·3 | | | | 0·063 | 0·17 | 0·14 | | | | | 112 | 250 | 70 | Means of composite samples from 2 "forest corridors" 30 years old, before and after clearing and burning. |
| | | | 0–4 | 5·9 | | | | 0·309 | 1·15 | 0·62 | | | | | | | | |
| 3 | Liberia | 80–180 | 0–3 | 4·5 | 2·37 | 0·146 | 8·9 | 0·77 | 1·31 | 0·62 | | 8·8 | | | | | | Mean of 94 samples under secondary forest before clearing. (3–6, 27 samples.) |
| | | | 3–6 | 4·1 | 1·35 | 0·083 | 9·2 | 0·17 | 0·59 | 0·38 | | 7·9 | 250 | (8) | | 250 | 27 | |
| | | | 0–3 | 5·3 | 2·77 | 0·154 | 18·0 | 1·22 | 2·67 | 0·90 | | 10·6 | | | | | | Mean of 54 samples after clearing and burning secondary forest. (3–6, 6 samples.) |
| | | | 3–6 | 4·0 | 1·62 | 0·101 | 9·2 | 0·42 | 0·51 | 0·29 | | 11·2 | | | | | | |
| 4 | Benin, Nigeria | 72 | 0–6 | 5·0 | 1·16 | 0·088 | | | | | 2·5 | 5·6 | | | | | | Means from samples of secondary bush 10 to 20 years old and over 30 years old, before and after clearing and burning. |
| | | | 6–18 | 4·4 | 0·66 | 0·054 | | | | | 1·4 | 5·3 | —120 | | | | | |
| | | | 0–6 | 5·9 | 1·23 | 0·090 | | | | | 3·5 | 5·9 | | | | | | |
| | | | 6–18 | 4·5 | 0 65 | 0·050 | | | | | 1·5 | 5·2 | | | | | | |
| 5 | Eriyagama, Ceylon | | 0–6 | 7·0 | 2·62 | 0·218 | 4·5 | | | | 20·3 | | | | | | | Jungle before clearing. |
| | | | 0–6 | 7·4 | 2·55 | 0·218 | 19·0 | | | | 25·6 | | 0 | 28 | | | | Same area after clearing and burning. |
| 6 | Rambawa, Ceylon | | 0–6 | 7·4 | 1·38 | 0·127 | 8·6 | | | | 12·4 | | | | | | | Jungle before clearing. |
| | | | 0–6 | 7·4 | 1·32 | 0·117 | 22·2 | | | | 11·1 | | —190 | 26 | | | | Same area after clearing and burning. |
| | | | | | | | | Estimates of Nutrients in Combustible Parts of Vegetation | | | | | | | | | | |
| 1 | Kade, Ghana | c.65 | | | | | | | | | | | | 65 | 450 | 1400 | 200 | 40 year old high forest. |
| 2 | Belgian Congo | c.75 | | | | | | | | | | | | | 196 | 134 | 80 | 5 year fallow. |
| | | | | | | | | | | | | | | | 233 | 170 | 90 | 15–16 year fallow. |
| 3 | Ejura, Ghana | 59 | | | | | | | | | | | | 7 | 41 | 31 | 22 | High grass savanna. Addition from grass only |

burning. Similar measurements were made on two other sets, each of 16 plots, at the same site. The only difference in the three sets of plots was in cultivation treatment. The results quoted in Table 8 are for the set that received no cultivation, in accordance with local practice at Kade. The other two sets received a light hoe cultivation and a deep hoe cultivation. The net increases of pH and nutrients on these plots were closely similar to those quoted, but the additions were more evenly distributed in the top foot of soil.

The increases in exchangeable calcium and potassium at Kade are much larger than recorded at other centres, although closely in accordance with the amount stored in the vegetation. The difference is probably due to the fact that much of the ash is liable to be removed from the surface horizon by the first rains, either through leaching or surface wash. At Kade one light rain only occurred after felling and burning and before taking the soil samples. It may well be that a longer interval and larger rainfall occurred between felling and burning and sampling in the other examples.

In the example from the Belgian Congo the soils were also sampled with particular care (Laudelout, 1954). The nutrient additions estimated from the soil differences following the clearing of two 30-year-old forest corridors were compared with those it was calculated would be released on burning similar forest fallows of varying ages, for which the data were presented in Table 2. The figures presented again allowed for the fact that the very large trunks and roots were not burnt. There is fair agreement between the two types of estimate.

Reed (1951) gives averages from large numbers of profiles sampled under secondary forest in the moist evergreen Liberian forest and from others sampled after burning (example 3). We have calculated the differences in lb. per acre. The additions agree fairly well with those from the Congo.

The changes following the clearing of secondary moist semi-deciduous forest over 30 years old at Benin, Nigeria, determined by Vine (Toovey, 1948), also agree well with the other examples. Only changes in the total nutrient cations were measured. In example 6 from Ceylon the absence of a rise in pH and the apparent fall in total exchangeable cations following burning is an unexplained anomaly.

In savanna the amounts of nutrients released on burning are very much less than in forest, and largely depend on the density of the woodland and the thoroughness with which it is burned. For comparison with the forest data the nutrients added in the ash of high-grass savanna are given. The amount of calcium is strikingly less than is added from the forest vegetation. No analyses of savanna soils before and after clearing have been noted, but it may be assumed that the effects of the ash will be similar to its effects in the forest, but on a reduced scale. Thus Coutts (1945) found a pH increase of only 0·2 unit on burning veld grassland in South Africa.

The large quantities of nutrients concentrated on a small patch of cultivated soil under the 'chitemene' system has already been mentioned (see p. 32).

In general all the data from forest indicate a substantial increase in the exchangeable cations in the soil, and a corresponding rise in the pH. Particularly on very acid forest soils this is one of the most important effects of burning. If it were possible to incorporate the organic matter of the fallow into the soil without burning the effect would be similar to a continued addition of litter: the humus level would rise and with it the exchange capacity, and the pH and availability of the cations would show little change.

The effects of burning on the soil organic matter have been much debated. Discussion has been confused by failure to distinguish between humified and non-humified material, and this has led to the statement that the humus is burned. Though many observers have noted that the litter layer is largely destroyed by the burn, there does not appear to be any loss of humified organic matter from the soil itself. The Ghanaian, Nigerian, Liberian and Ceylonese data do not indicate any significant changes in the carbon and nitrogen contents following burning. Riquier (1953) compared 6 profiles in "primary" forest in Madagascar with 6 profiles taken from an adjoining plot 3 months after clearing. The "on-the-surface" sample shows a marked loss of organic matter and nitrogen, but this consisted largely of unhumified material. At 4 in. there was little change. Richards (1952) has quoted the work of Duthie, Hardy and Rodriguez on the changes following clearing of an area in the Arena Forest Reserve in Trinidad. This apparently shows a substantial loss of carbon and nitrogen on clearing before any burning. In an appendix to their report (abridged by R. L. Brooks, 1937) it is pointed out that later sampling showed that the cleared plots had initially a lower carbon and nitrogen status than the uncleared plots, so the effect cannot be regarded as proved.

### (b) Secondary Effects

These arise from the effects of heat on the soil and from the influence of the pH change and nutrient additions on the soil population.

We have found no records of soil temperatures during the burning of felled forest vegetation. An indication is given by the measurements of soil temperatures attained during the burning of dense cleared gorse and manuka thicket in New Zealand (Miller *et al.*, 1955). Except where wood was piled even the surface soil was little affected, and this accords with our general observations. Where wood was burnt in heaps temperatures of 100°C were recorded at 2 in. and 60°C at 4 in. The general result is that the burning of the forest vegetation has little effect on the general expanse of soil, but in patches where logs and heaps of wood undergo

prolonged burning the surface inch or two of soil may undergo profound change.

The effects of heating in the top inch or so of soil may be more general on plots cultivated under the 'chitemene' system (see p. 32). The uniformly piled branches leave a thick cover of ash which remains hot for some hours. The crop is planted into the ash and baked soil. The heating promotes an improved structure in the top 1 or 2 cm. (R. Webster in discussion). It also leaves a weed-free seed bed on terrain that has a herb layer of grasses under natural conditions. Conklin (1957) in the Philippines has also noted that the surface soil is rendered more friable after burning the forest. The soils in the area he studied were predominantly heavy and sticky and appear to contain much 2:1 type clay. He also noted that the uniform layer of surface ash discourages the industrious armies of small reddish seed storing ants which can remove more than 5 litres of seed rice from a newly planted plot in one night.

For grassland fires Cook (1939) found in South Africa that the burn barely affected the soil temperature at 2 inches, although the surface temperature attained 550 C for 6 minutes. Masson (1948) in Senegal found an increase of only 14·4 C at 2 cm. Heyward (1936), in a study of 44 grass fires in the longleaf pine forest area of the south-eastern United States, recorded temperatures of 70–85°C in the upper $\frac{1}{4}$ in., up to 90 C in an extreme case at $\frac{1}{2}$ in. and only slight increases of temperature at 1 in. depth. Many others who have observed running grass fires in savanna have commented on their slight effects on the soil, e.g. Milne, quoted by Waldock, *et al.* (1951), and Henrard (1939).

The effects of grass fires on the soil may be greater in the system of 'hariq' cultivation practised in parts of the Southern Sudan (Tothill, 1940). The soil is clay and the grass coarse and long. It is allowed to grow for 2–4 years without firing. The thick mat which accumulates is fired after the first rains of the year of cultivation. The young grass shoots are killed by the fire and no further hoeing is needed.

Although the actual temperature rise in the soil may be small, it can have an important effect. It is well known that the fertility of a soil is increased by heating, even to temperatures as low as 45 or 50°C. Russell (1950) quotes references from Vergil's Georgics and the Vedas on the good effects of soil heating, and a great deal of work has been done in recent years on the reasons for the effect (cf. the review of Partial Sterilization in *Soils and Fertilizers*, 1948). Wherever the heating is produced by the burning of organic matter on the soil the interpretation of the effect is complicated by the fact that nutrient addition, pH increase, removal of vegetation and heating all occur together. The effects of heating alone have, however, been studied by Mukerjee (1954), using Indian and English soils. He has summarized the results of his work and that of others on the subject. It is generally agreed that plant growth is better in previously heated

than in unheated soils. Any seeds present in the soil during the heating are liable to be killed or to have their germination retarded. The supply of available nutrients in the soil solution is increased by heating, and in particular the rate of nitrogen mineralization is generally greater subsequent to the burn than before it. In most instances there is a profound change in the numbers and composition of the microflora of the soil.

The effect of heat on the microbial population is usually referred to as 'partial sterilization', and it is similar to effects produced by drying or by treating the soil with antiseptics. The sterilizing treatment leads to an initial decrease in the microbiological population, after which it redevelops, usually with a modified composition, to a level greater than before. From the soil-fertility viewpoint the most important effect of the increase is the change in the rate of nitrogen mineralization. This generally shows parallel changes to the population changes.

In the forest zone on a highly acid oxysol in Malaya, Corbet (1934) observed an increase in population on burning from under 1 million to 11 million micro-organisms per gram of soil. Even the higher figure is surprisingly low. The increase only persisted for a few weeks. He attributed the increase primarily to the increase in pH and increased availability of nutrients, as similar increases were observed on areas to which the wood ash was blown, but which were not actually subject to heat. Dommergues (1952*a*) has observed corresponding increases in similar circumstances in Madagascar, and records that there is an eventual decrease in the soil population, which would seem to be associated with the gradual loss of the nutrients added in the ash and the declining pH.

The fact that the changes in ochrosols, which are near neutral and reasonably well supplied with nutrients before the burn, are very much less pronounced than in the oxysols (Laudelout and du Bois, 1951; Dommergues, 1954*b*) also suggests that the nutrient additions and pH change are more important than the effect of heat. Dommergues (1954*a*) suggests that the stability of the soil population in the ochrosols should be used as a criterion to distinguish them from the acid forest soils where the population is highly unstable.

In the savanna zone where the quantities of nutrients added by the burn and the pH increase are much smaller, there is generally relatively little change in the soil population following the burn (Henrard, 1939; Dommergues, 1954*c*; Meiklejohn, 1955). An immediate decrease in total numbers is usually followed by a gradual increase to about the former level. The numbers of nitrifiers may, however, show an increase since Dommergues (1954*c*) reports this following the clearing and burning of wooded *Andropogoneae* grassland, and Berlier *et al.* (1956) obtained similar results following the clearing of a grassland area in the southern part of the Ivory Coast. In Kenya, Meiklejohn (1955) found that the nitrifiers for the first month (a completely dry one) after the burn were virtually

absent. She was working on an area of rough grass which had been established three years following native cultivation, and was subject to annual burning, and also on an area of wattle. As will be discussed later (pp. 109–110) grasses themselves exert a repressive effect on nitrification, and it may be that an increase in nitrifiers is related to the removal of vegetation, rather than any direct effects of the burn.

To sum up—burning is an essential preliminary to cultivation in both forest and savanna. The carbon, nitrogen and sulphur in the fallow and litter are lost in the burn, but not the amounts in the soil humus. The alkaline ash raises the pH and availability of cations in the surface soil, a very important effect on acid soils. The direct effects of heat on the soil are confined to local spots where the wood is piled. This may have some direct effect on the availability of nutrients and the soil population, but it is much less than the effects of the pH change and nutrient addition.

## Chapter 6

## THE DECLINE IN FERTILITY UNDER CROPPING

It is generally thought that fertility declines rapidly with successive seasons of cropping. Before analysing in detail the nature of the decline we need to consider just how rapidly yields fall in the different regions.

In the forest region, there is no doubt about the rapid decline. The yields in the first and second cycles of a rotation of rice, groundnuts and cassava and a one-year leguminous cover crop succeeding a forest fallow in the Belgian Congo (Tondeur, 1956, p. 60) were:

| | Yields (kg./ha.) | |
|---|---|---|
| | 1st cycle | 2nd cycle |
| Rice | 2,341 | 565 |
| Groundnuts | 1,362 | 191 |
| Cassava | 45,000 | 30,000 |

In the forest region of Ghana (60–80 in. p.a.) 6 fertilizer trials have been maintained for 8 years under a continuous 2-year rotation of maize and cassava. In the absence of fertilizer effects, the yields of both crops in the fourth cycle were just under half the yields in the first cycle which followed clearing of mature secondary forest (Nye and Stephens, 1960).

Grist (1953) estimates that virgin land in Malaya will produce 1500-2000, 1200, 800 lb. per acre of paddy in successive years. Milne (1940) describes the rapid fall in the yields of food crops following clearing of forests on sandy soils in British Guiana and Trinidad. Charter (1941) estimates the yields of maize on peasant milpas in British Honduras as 1000-800, 800 600, 600-400 lb. per acre in successive years. Popenoe (1957) reports that the yields of a second

crop of maize in north Guatemala are often reduced to one half those of the first crop. It is evidence such as this that has led to the usual view of the ephemeral fertility of tropical forest soil.

In regions with rainfall under 60 in. all our information comes from experimental stations. Such results differ from those that would be obtained on peasant farms because plots are kept well weeded and unusual sequences of crops are grown. The weight of evidence is that yields decline more slowly than in the wetter regions.

At Ibadan, Nigeria, (49 in. p.a.) on soils developed over medium-grained biotite gneiss on land newly cleared from secondary thicket, yields were fully maintained for 8–11 years in 4-year rotations which involved only one, two or three green-manure crops in a total of eight (Vine, 1953) (rotations V, IV, III 1923–30/39). After twelve years the yields of the most intensive rotation declined markedly.

Numerous fertilizer trials in the savanna zone of Ghana (40–60 in. p.a.) have shown that, on the average, yields in the absence of fertilizer effects fall only slowly (under 25%) over a period of 9 years (Nye and Stephens, 1960).

In the elaborate rotation trial on light granitic soil at Serere, Uganda, (c. 50 in. p.a.) that has been in progress since 1936, decline in fertility is remarkably slow. One set of treatments compares 1, 2 and 3 years of rest in a rotation period of 5 years. A year of rest rather than crop results in an increase of approximately 10 lb. per acre of seed cotton—a very small amount when the mean yield is around 600 lb. per acre. The effect of the rest in successive years is additive. That this soil has high inherent fertility is indicated by the relatively small responses being obtained from farmyard manure (unpublished report by W. R. Mills, 1958).

Rather more rapid declines have, however, been noted in other savanna regions. At Kano, Northern Nigeria (35 in. p.a.) on a light granitic soil plots have been maintained since 1931 under continuous groundnuts, continuous early-maturing millet (*Pennisetum* sp.), and continuous late-maturing sorghum. Half the plots received no manure, and the remainder 3 tons per acre of farmyard manure every year. Average yields in successive 5-year periods have been as follows (priv. comm. Director of Agriculture, 1959):

(lb./acre per annum)

| | Groundnut (kernels) | | Millet (grain) | | Sorghum (grain) | |
|---|---|---|---|---|---|---|
| | — | F.Y.M. | — | F.Y.M. | — | F.Y.M. |
| 1931–35 | 906 | 1145 | 823 | 1039 | 485 | 1018 |
| 1936–40 | 700 | 1005 | 406 | 746 | 293 | 905 |
| 1941–45 | 623 | 906 | 284 | 587 | 94 | 841 |
| 1946–50 | 288 | 566 | 487 | 940 | 81 | 834 |
| 1951–55 | 456 | 757 | 295 | 771 | (to 1949) discontinued | |

At Yambio Experiment Station, Southern Sudan (58 in. p.a.) yields of cotton, groundnuts and eleusine dropped sharply after

3 years' cropping (Anthony and Willimott, 1956). Yields of cotton expressed as a percentage of the yields on first and second year land on the whole station were in successive years: 127, 130, 114, 75, 57, 53 per cent.

At Namulonge, Uganda (43 in. p.a.) there has been a steady decline in fertility on land cropped continuously with two crops a year. In the main rotation trial yields of seed cotton after 6 years' continuous arable averaged 835 lb. per acre compared with 1154 lb. per acre in the first year after a 3-year ley (Lea and Passmore, 1958).

As has been said, all these results have been obtained on plots at experimental stations where the land has been well weeded. It will be shown in the next section that the farmer does not find it profitable to weed thoroughly for many years if he can shift to other land. It will also be shown that in the absence of weed effects the differences in the rates of decline of yields on savanna soils seem likely to be related mainly to differences in the rates of decline of phosphate availability.

We have now to consider the reasons for the decline in yields, and the reasons that lead a farmer to abandon one piece of land and clear another.

Cropping is likely to have the following consequences, whose importance will be assessed in turn.

(a) Multiplication of pests and diseases
(b) Increase of weeds
(c) Deterioration in the physical condition of the soil
(d) Erosion of top soil
(e) Deterioration in the nutrient status of the soil
(f) Changes in the numbers and composition of the soil fauna and flora.

The effect of cropping on the rate of loss of humus and its effect on the microbiological population of the soil are so closely linked with the changes in the nutrient status of the soil that they are considered in that section (e). Changes in the humus that are reflected in the physical conditions of the soil and its erodibility are considered under these headings.

### (a) Pests and Diseases

The long rest given to the land during the fallow, the scattered distribution of the small plots, and the fact that one kind of crop is rarely grown more than once in each cropping period—all these factors serve to check the build-up of pests and diseases, and it is seldom that the period of cropping is curtailed because of them. Pests and diseases might well multiply if the cropping period was extended so that one crop was grown at frequent intervals. For example, in the forest region of Ghana, it is possible to follow the maize planted in the early rains with a second crop in the late rains. When this is done the second maize crop will frequently be seriously affected by corn-stalk borer (Bowden, 1956). Traditionally the

farmer has not planted a second crop of maize, possibly for this reason. Again, in the savanna region, the opening crop is frequently yams. A second yam crop is rarely grown; when it is, it is often seriously affected by yam beetle (*Heteroligus meles* and *H. claudius*). Experiments described by Cutting *et al.* (1959) in Nyasaland, where 'head smut, stalk borer and striga in maize, and root eelworm of tobacco are rampant in areas of prolonged African cultivation', have shown clearly the advantage of rotations. Maize, groundnuts and tobacco all yielded better in rotation than in monoculture. Indeed, the advantages of rotational systems in controlling pests and diseases seem in general to be reflected in customary native cropping sequences.

(b) Weeds

There is no doubt that the increasing effort of keeping the land free of weeds as the cropping period proceeds is often the primary reason for a patch of land being abandoned. As a preliminary to a brief survey of the importance of weeds in the different ecological zones there are four points to be made.

First, a farmer will tend to abandon a plot when the return from the considerable labour of clearing and cultivating a new one exceeds the return from his labour in weeding the existing one. In a situation where there is abundant land, and little incentive to produce a surplus for sale, infestation with weeds does not have to be so severe that it is impossible to continue cropping, but merely sufficient to make it easier to obtain subsistence by clearing new land. The timing of operations also plays an important part. Clearing is done in the dry season when the farmer has little else to do. By clearing fresh land then, he reduces the work of weeding at a busier time of the year, and so spreads his labour more evenly.

Second, the sequence and combinations of native crops, and other cultivation practices, are usually admirably adapted to control weeds with the least effort. The explanation of native practice is as often to be found in the problem of weed control as in the physical and chemical properties of the soil.

Third, land is often recognized as ready for clearing again when certain plant communities have become established, indicating that the weeds proliferating during cultivation are suppressed.

Fourth, it is frequently difficult to decide whether falling yields are due to weeds or to declining fertility. Poor crops tend to be weedy; are the weeds the cause or the effect? The following passage about Samoa illustrates the difficulty of interpreting accounts: "After about 3 taro crops (or two years of cultivation) declining yields forced the Samoans to abandon their clearing to the increasing weeds and regenerating second growth . . ." (Watters, 1958).

The difficulty of keeping on top of weeds differs greatly both between climatic zones and between continents. Before discussing these differences in the forest regions it is useful to recognize two

types of rainfall distribution. In the equatorial type the rain is fairly well distributed through the year, often with two peaks, and the dry season or seasons are mild. In the monsoon type, typical of regions further to the north or south of the Equator, the rain is concentrated in a single peak and the dry season is fairly severe. The well distributed epuatorial type encourages the growing of semi-perennial crops such as plantain. In the monsoon type the main crops are annuals, and as will be seen, the control of weeds is more difficult.

In the equatorial forest regions of Africa the description of native practice in relation to forest regrowth—the 'weeds' of the cropping period—in the central Congo Basin by Tondeur (1956) accords with our own experience in West Africa. Immediately following the clearing and burning of the forest the land is bare. During the growth of the first cereal crop, a great diversity of weeds springs up. A detailed analysis of them has been made at Yangambi (Bernard *et al.*, 1949). They consist of grasses and other herbs, herbaceous and woody lianes, forbs, shoots from roots and stumps, and tree seedlings derived from the cleared forest and from surrounding areas. As the crop has a good start the labour of weeding is not heavy. Keay (1959) has suggested that one advantage of leaving the soil as undisturbed as possible on clearing the forest is that the many dormant weed seeds are not encouraged to germinate. When the cereal is harvested the interplanted semi-perennial crops like cassava, cocoyam and plantain soon establish a good cover, and there is little difficulty in keeping them above the weeds until they mature in the second year. These semi-perennials and unharvested cassava remain into a third or fourth year until the regrowing forest is allowed to overwhelm them.

Though variable in detail the essential points of this cropping system are the following.

The only period during which the land is without a cover of crops is immediately after the heavy burn when the land is at its cleanest. Thereafter the short-term and long-term crops overlap, and their shade is sufficient to make the task of weeding a relatively light one. The most aggressive competitors are the woody species which can thrive in light shade, and are readily controlled with a slash of the cutlass, their litter helping to protect the soil. Grasses, and similar weeds that need to be destroyed at their roots, never gain a firm hold so long as the preceding fallow is good and the land is clean at the start. The thin cover of low-growing weeds that is usually present after the first few months is probably more of a help in protecting the surface of the soil, between the widely spaced stems of cassava, plantain and cocoyam, than a check to their growth. It seems likely that in most cases cropping with semi-perennials could be prolonged. However, since fresh land must be cleared for more highly valued crops such as maize or rice, the farmer has little incentive to continue producing more starchy foods than his family

wants to eat. As it is, a great deal of the cassava and cocoyam planted is never harvested, being regarded merely as an insurance against need.

We conclude, therefore, that in equatorial regions in which semi-perennial crops are grown, weeds are not the reason for the land being abandoned, except in so far as they make the planting of a second cereal crop during the cropping period a laborious business, and thus encourage the farmer to clear fresh land.

Sierra Leone is an example of a region in Africa where the rainfall distribution is more nearly the monsoon type. Here rice is the first crop, and traditionally it has been interplanted with other annuals and cassava, and the land abandoned in the second year (Waldock *et al.*, 1951). There is, however, an increasing tendency to follow rice in the first year with groundnuts and fundi, *Digitaria exilis*, in the second year. A second planting of short-term crops such as this causes a marked decline in the rate of regeneration of the woody fallow, for the clearing and burning in the second year kills the suckers and seedlings. In marginal areas of the forest the practice leads to establishment of grasses.

No descriptions suggest, however, that the farmer would find the normal invaders of forest land impossible to control if he continued cropping with annuals. Thus Bergeroo-Campagne (1956), in his detailed study of the N'Dranouas of the Ivory Coast, writes of cultivation on the edge of the forest zone with a succession of annual crops:

> "The end of cultivation is due to lowering of yields and the desire of obtaining a good secondary regrowth of fallow. It does not seem that invasion of weeds plays a role: *Imperata* comes in little if at all, and other adventitious plants are easy to weed." (Authors' translation.)

Emerson (1953) gives interesting details of the influence of weeds on the "milpa" system in tropical America, in which successive crops of maize, mixed with beans, are grown. In the northern part of the Yucatan Peninsula the rainfall is around 50 in., and is concentrated in a 5-month rainy season. The land is under 'bush'—a woody fallow reaching 30–50 ft. after 10–20 years and containing few annual weeds and almost no grasses. Cropping is rarely more than two years and the fallow averages 10 years. A man can clear 1/5 acre of bush in a day for the first milpa and it takes him the same time to clear the weeds and sprouts for the second-year milpa. He can weed about 1/10 acre a day, though the second milpa is always more weedy than the first. In all, an average family holding of 4 acres will occupy the milpero for a total of 80 days only, this total including an allowance of 20 days for planting and harvesting. The second crop yields less than the first, probably because it is more weedy. It is therefore easier to clear more land than to continue cropping the old plot. The length of fallow is sufficient for the trees to reach a convenient size for cutting with an axe and to choke out

small bush and weeds. Emerson considers the cropping period could be extended if pressure on the land required it, but pressure at present is slight. In the same area Morley (1946) notes that the practice of the ancient Maya was to pull out weeds by the roots rather than chop them with a cutlass. This more thorough weeding has been shown experimentally to bring about a marked increase in yield in a four-year-old milpa. Morley considers that the difference between ancient and modern methods of weeding is probably chiefly responsible for the fact that to-day Maya cornfields are planted for only two consecutive seasons, whereas formerly they were probably used for four or five, or even more, consecutive years before they were abandoned.

In the forest of British Honduras, Central America, maize is grown in successive years on fertile limestone soils. Charter (1941) notes that 'alang-alang' or bracken infests the land after a year or two, and suggests this is the cause of declining yields.

In these examples from the forest regions of Africa and America under a monsoon climate it appears that extension of cropping with annuals is undesirable and is rarely practised because of increasing difficulty in controlling grasses, and the weakening of the woody regrowth. Where a succession of crops is grown, weeds seem to be mainly responsible for declining yields.

In the forest region of south-east Asia there is no doubt that the weed problem is paramount. Pendleton (F.A.O., 1948) with a lifetime of experience in this area writes of south-east Asia generally:

> "Usually, the kaingin is abandoned after the harvest of the first planted crop, because during the growth of the second crop the infestation with weeds, particularly with cogon, is so serious that the labour needed for weeding is excessive . . . The length of time the land is allowed to remain in forest depends upon how soon the forest can choke out the cogon and other weeds."

Conklin (1957) estimates that a Hanunoo farmer spends 300 man-hours per hectare in weeding first-year land cleared from primary forest, and 600 man-hours on land cleared from secondary forest about 20 years old. The location of the plot in relation to surrounding areas of grassland or forest is important in controlling the incidence of weeds and the regeneration of forest. Thus soils on ridges lying above the surrounding forest and exposed to wind are readily colonised by the light wind-borne grass seeds. Freeman (1955) gives details of the relation between the length of the crop and fallow in Sarawak and the invasion of cogon, *Imperata cylindrica*. Provided one crop of rice only is taken, a fallow of 12 years is the minimum safe period to maintain its growth. If rice is grown in successive years, which involves a second clearing and burning of trash and consequently destruction of regenerating seedlings and suckers, the fallow must be well over 15 years. The farmers themselves give weeds as the reason for leaving the land—they do not suppose the soil is in any way incapable of bearing further culture. Hutton (1921*a*, *b*) who made a detailed study of the Nagas in Assam

came to the same conclusion. Joachim and Kandiah (1948) concluded from their analyses of soils under the "chena" system in Ceylon that land is abandoned because of weeds and not because its fertility has fallen too low.

The importance of weeds in south-east Asia is due to the aggressiveness of the Asian form of *Imperata cylindrica*, and also to the high value placed upon rice. If the dry season is not severe, cropping can be prolonged if farmers will follow the rice crop with semi-perennials whose cover will keep the grasses in check. For example, though the Hanunoo lavish most care on the rice crop, roots and bananas form 60% of their diet (Conklin, 1957). After the rice harvest these crops occupy the ground on the average for two or three years and in some instances up to 12 years. It is not clear whether farmers allow the land to return to fallow because the yields of these crops are declining, or because they have more of them than they need and must clear fresh land for rice.

We may now turn to the savannas. In Africa, *Imperata cylindrica* is a serious pest on the forest margins. In West Africa this is the main zone of yam (*Dioscorea* spp.) cultivation. The yams are usually followed by one or two years of short-term crops, and cultivation may be ended with a planting of cassava. Bergeroo-Campagne's (1956) account of this zone in the Ivory Coast accords with our own observations in Ghana. The *Imperata* becomes increasingly aggressive as cropping is prolonged. The more fertile the soil the more difficult it is to control. Yam tubers are pierced by the sharp-pointed leaves (the local name is spear grass) and rot sets in. When the land is abandoned perennial grasses, notably *Andropogon gayanus*, gradually displace the *Imperata*, even if burnt annually, and the farmer judges when the land is ready for further cropping by its disappearance. In parts of British Honduras when the cassava fields become infested with *Imperata braziliensis* the farmers deliberately plant a wild sugar cane *Gnerium sagittatum* to swamp it (Charter, 1941). In this respect the *Imperata* spp. of Africa and America differ from the species which dominates the fire climax in south-east Asia.

In the elephant-grass zone of Uganda *Imperata cylindrica* is also a nuisance, but the peasants find little difficulty in eradicating it by repeated hoeing in the cotton fields. In this zone 'lumbugu', *Digitaria scalarum*, with deep underground runners is more serious, and leads farmers to abandon their plots until it has been repressed by the regrowth of elephant-grass (Thomas, 1940).

Over the greater part of the African savanna, *Imperata cylindrica* is scarcely a problem. In these drier areas weeds are less commonly the reason for the land being abandoned to fallow than declining fertility. The parasitic weed of cereals—*Striga*—is probably the most important pest (e.g. Hayes, 1940; Milne, 1947).

The importance of timely weeding of annual crops is shown by some typical results quoted by Cutting *et al.* (1959) in Nyasaland.

Maize yielded 3816 lb. per acre when weeded four weeks after germination, but only 2866 lb. per acre when weeded six weeks after germination.

(c) Physical Conditions in the Soil

Those physical properties of the soil that affect its fertility and may deteriorate with cropping are covered by the term 'soil constitution' (Clarke, 1956). The constitution of the soil is governed by the size and continuity of its pores. It is these which determine its permeability and drainage characteristics; the amount of water it stores for crops when drainage has ceased; and the exchange of carbon dioxide and oxygen in the root zone. The constitution of the soil is closely linked with its erodibility, which will be considered in the next section.

Discussions of the effects of shifting cultivation on the physical properties of the soil are full of references to the degradation of the structure of the soil, without precise recognition of the kind of structure that is needed. Furthermore, the emphasis on structure directs attention to soil aggregates and away from the all-important voids which lie within and between them. Russell (1958) emphasises the pore space, and states that "it has been found by experience that a soil will have a very favourable distribution of large pores if it is in the form of crumbs between about 0·5 and 3 mm. in size." Such a desirable constitution is built up in the top soil under a forest fallow, and also to a lesser extent in the subsoil. The constitution promoted by savanna is less favourable. The reasons for the differences will now be described.

Under a forest fallow the surface of the soil is covered by a thin litter layer of twigs and leaves about $\frac{1}{2}$ in. thick. The rapid rate of decomposition of litter has already been described. At the base of the layer the litter is highly decomposed and merges into another $\frac{1}{2}$-in. layer containing a mixture of highly decomposed debris, mineral matter brought up by ants and termites as they consume the litter, and the excreta of the soil fauna: worm casts are often conspicuous on neutral and slightly acid soils, their broken remains imparting a coarse granular structure. The mixture is full of fungal hyphae and fine rootlets. The top two inches of the mineral soil proper is humic and very porous; it has a granular or crumb structure, and is soft when dry, and very friable when moist. The whole of this layer is being constantly stirred by termites and other fauna. It is full of channels and often contains relict casts. Below 2 in. the humus staining is much less apparent, the colour brightens, the porosity and crumb structure are noticeably reduced and the soil becomes heavier and more compact, though traces of insect and worm channels remain. The concentration of humus in the surface 2–3 in. is clearly shown by the analyses of forest soils presented in Table 3.

Determinations of the porosity of tropical forest soils are scarce. The density of successive layers of the Kade forest soil in Ghana has

been found to be 232, 357, 391, 380 thousand lb. of oven-dry soil per acre per in. in the 0–2, 2–6, 6–12, 12–24-in. layers, respectively.

Under both high-grass and tall bunch-grass savanna the constitution developed is much less favourable because the soil is exposed to the early rain, because there is less litter to encourage insects, and because the humus content is lower. The much less rapid change in the humus content with depth in savanna compared with forest soils is illustrated by the data in Table 3. The change in porosity with depth is also less marked. A favourable condition may, however, be developed beneath unburned vigorous hygrophilous grasses, notably elephant grass. Martin (1944) has described the increase in water-stable aggregates promoted by a number of East African grasses, though the value of the test used is doubtful (Pereira, 1955); and Rowland (1955) has stressed the improvement in 'heart' and workability that is promoted by a well fertilized grass ley in Southern Rhodesia. Such grasslands, however, occupy a relatively small area.

We may now examine the effect of cropping on the constitution of the soil.

On clearing and burning the fallow, the surface of the soil is bared to the sun and rain until the first crop forms an effective cover. Deterioration during this time is rapid. In forest soils, which are little disturbed by cultivation, the impact of the rain drops on the bare surface shatters the aggregates and seals the pores with suspended silt. The unhumified organic matter in the immediate surface, which serves to keep open the pores, decays rapidly. This decay cannot necessarily be attributed to the effect of increased insolation, since the normal rate of decomposition of litter under a fallow (p. 40) is quite sufficient to account for its rapid disappearance.

It must be emphasised that the decline in the favourable constitution of the surface layer over the first few weeks has little to do with the decomposition of the true humified organic matter, which is a slow process. Thus Pernet (1952) separated the humified from the non-humified material with a bromoform and benzene mixture of S.G. = 2·0, and showed that the very rapid decline in organic matter in the immediate top soil is due to mineralization of the unhumified finely comminuted litter. Once an effective cover is formed the decline in constitution is arrested. All weeds are slashed and their litter helps to protect the top soil. The hoe is not used, so its surface, still fairly open, remains undisturbed. Further decline depends entirely on the extent to which the surface is exposed during subsequent cropping, a matter that has already been discussed.

In savanna the surface of the soil is very much more thoroughly disturbed on clearing than in forest, because of the need to clear it of grasses. Frequently it is worked with a hoe into mounds or ridges, and the first crops are planted into loose freshly hoed earth. This condition is rapidly destroyed, and a hard surface 'cap' often develops, which impedes the entry of oxygen and promotes run-off.

Throughout the cropping period the soil is repeatedly disturbed. Only the surface is broken by the numerous weedings, but a more thorough cultivation is usually needed before each planting season. Kellogg (1948) has stated that tropical soils more commonly become overgranulated with excessive cultivation. While this effect may occur on some rubrisols (p. 23) it does not appear to be general.

The quantitative study of changes in the constitution of the soil has been greatly hindered by lack of experimental measurements that mean anything in terms of field behaviour (Pereira, 1955). Pereira (1956) has developed a rainfall acceptance and transmission test which is a considerable advance on earlier methods. He and his associates (Pereira *et al.*, 1954) found that on an earthy red latosol (46% clay) over a granitic rock at Kawanda, Uganda (43 in. p.a.), the favourable constitution developed by a three-year rest under 3 species of grass—*Pennisetum purpureum*, *Paspalum notatum*, and *Chloris gayana*, was largely lost after one year of cropping. On Kikuyu red loam (63% clay), a red latosol derived from trachyte, most of the substantial benefit conferred by four years of rest under *Pennisetum purpureum* was lost by clean cultivation under coffee for two years.

These East African experiments have been carried out on soils with a fairly high clay content and with vigorous fallows of *P. purpureum* among other grasses. The savanna soils in Africa as a whole do not have such a good chance of building up a structure. We have observed that the effects of a rest under the common tussock grasses of the high-grass and tall bunch-grass savanna are even more transient, once the land is cleared. This is specially so on the widespread light top soils commonly developed over quartzose rocks. On such soils in Ghana, Stephens (1960*b*) has conducted percolation and splash tests in the field. He found no differences between cropped plots under rotational grass fallow and seven years of continuous cropping.

When the ephemeral constitution built up in the surface layer under the fallow has been shattered by rain, the extent to which the deterioration will continue depends largely on the inherent constitution of the soil. The properties which govern this are little understood, but it seems likely that the bonding of individual soil particles into micro-aggregates by iron oxides is particularly important.

It is a common experience with kaolinitic tropical soils that those with a red colour—an indication of unhydrated or slightly hydrated ferric oxide—maintain under frequent cropping a much more satisfactory constitution than those of comparable texture and humus content, but with a paler colour. Hardy (1933) has reviewed earlier observations on this point; and two of the criteria of a 'latosol'—a "relatively high degree of aggregate stability", and a "red colour or reddish hues of other colours" (Kellogg, 1950)—exemplify it.

To what extent all red soils or only some red soils show this favourable inherent constitution is still uncertain. That a high

macroporosity may be promoted by free ion oxide rather than organic matter has been demonstrated for terra rossa and rendzina soils in South Australia by McIntyre (1956). The contrast between a soil liberally supplied with ferric oxide and one less well supplied is illustrated by Pereira's (1954) finding that a continuously cropped Kikuyu loam maintains a better percolation rate than the soil over Kawanda granite only one year after grass rest.

There is a general impression that continuous cropping leads to lack of 'heart' in the soil. Though this is frequently ascribed to a fall in the organic-matter content, it is far from certain that it should be, nor is it known to what extent lack of 'heart' implies low yields. The question is complicated by the fact that poor yields due to low nutrient status may in themselves promote a poor physical condition because of poor cover, and low return of litter and root residues. Conversely high yields induced by fertilizers may maintain an excellent constitution, as shown for example in Southern Rhodesia on heavily fertilized soils growing maize continuously.

To break down this problem we need to know

(a) how far constitution declines with cropping;
(b) how far decline in yields is directly caused by decline in constitution;
(c) how far decline in constitution is due to decline in humus, and how far to exposure, tillage, etc.

We cannot answer these questions until the elements that make up soil constitution are better defined and measured on a variety of trials.

The evidence of long-term rotation trials in savanna is that, provided nutrient supplies are maintained, yields do not fall. From the results of many factorial fertilizer trials in Ghana (Nye and Stephens, 1960), and in Nigeria (Obi, 1957) all conducted on light savanna soils, it can be calculated that yields of a continuous rotation of crops on plots receiving complete inorganic fertilizer would be maintained for at least 6–9 years.

On a light soil at Ibadan, Nigeria (49 in. p.a.) maize has been grown in the first season and *Mucuna*—a leguminous cover crop—in the second for 20 years (Vine, 1953). Yields have been maintained without fertilizer, and it has made no difference to the yields or the apparent physical condition of the soil whether the *Mucuna* was burnt or dug in. The difference in total nitrogen content between the burned and unburned plots (0·100% dug in and 0·071% burned) showed in the level of nitrate, but not in the constitution of the soil.

Forest soils are sometimes tilled in the same way as savanna soils, the hoe being used for cultivation and weeding, and a succession of short-term crops grown, e.g. in parts of Sierra Leone (Waldock *et al.*, 1951). Our observation is that such treatment rapidly reduces the constitution of the forest soil to that of a savanna soil. Some idea of the importance of the change in constitution in lowering productivity may be derived from trends in yields on land

cleared from forest and cultivated continuously with addition of mineral fertilizers to maintain nutrient levels. Six such trials under a rotation of maize and cassava have been conducted on light textured forest ochrosols and oxysols in Ghana (Nye and Stephens, 1960). From the factorial effects it is calculated that yields of maize and cassava on plots receiving complete NPKCa fertilizer declined from 1,600 and 14,000 lb. per acre in the first and second year following clearing of the forest to 1,000 and 10,000 lb. per acre in the seventh and eighth. The decline is by no means catastrophic and may in part be due to insufficient or unsuitable combinations of fertilizers. With a grass mulch in addition to the fertilizer treatments yields were maintained. On sandy alluvial soil and a sandy clay yellow plateau latosol in the central Congo basin under continuous cultivation for seven years (14 crop seasons) with a number of combinations of short-term crops, yields have been maintained with a compound mineral fertilizer alone (Culot and Meyer, 1959). In both the Ghana and Congo trials yields on unfertilized plots fell very low.

In summary it seems that the constitution of the soil is very largely an 'inherent' quality, though in the surface horizon it may be greatly improved by a forest fallow or an elephant-grass fallow, and to a much smaller extent by typical high-grass and tall bunch-grass fallows.

The traditional system of cropping forest soils preserves at least part of the improvement promoted by the forest fallow; but where the hoe is introduced in cropping forest soils, the improvement disappears rapidly, and the conditions found in savanna soils are attained.

The native systems of cropping savanna soils rapidly destroy any small improvement promoted by the fallow. Thereafter with continuous cropping the constitution of the soil may possibly undergo a further gradual decline, but there is no sound evidence as yet that this is a cause of declining yields.

(d) Erosion

In any discussion of soil erosion it is necessary to distinguish between the natural erosion which will occur under the climax vegetation of the region, and the accelerated erosion which may be caused by cultivation. The general effects of removal of the vegetative cover have been so often described that there is little point in repeating them here. What is not so widely appreciated is the relation between the slope forms which are developed as a result of natural erosion and those which are stable under the changed conditions of cropping. Whereas cropping represents a drastic departure from the natural conditions under which the slope forms of the forest were developed, it is not nearly so drastic a departure from the conditions under which the slope forms characteristic of the

vast sub-humid landscapes of the savanna were evolved. The study of accelerated erosion is in fact an extension of the study of geomorphology.

The two (generalized) forms of landscape developed in (1) humid regions under forest vegetation and (2) in sub-humid regions are shown in Fig. 6. It is probable, but not proved, that the second

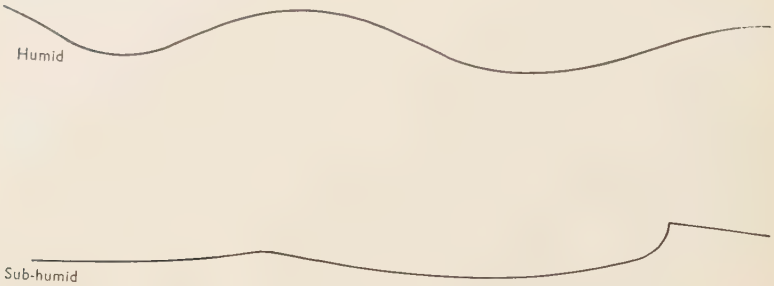


Fig. 6. Erosion forms of tropical humid and sub-humid regions.

form will develop only in conditions when the surface layer has no protective litter. Such conditions are associated with savanna grassland and may also occur under dry thicket and 'Miombo' woodland.

In the humid regions the dominant process responsible for transport of the weathered mantle is soil creep—to valleys which are deepened and broadened by the action of streams and rivers. The land form associated with creep is always convex in form.

In the sub-humid regions the dominant process responsible for transport is surface wash by water flowing in a sheet over the surface. This leads to slopes that are concave, in the typical form of a graded river.

Under forest transport by creep predominates owing to the ready percolation of rain into the soil and the reduction of sheet flow, and the resistance of the soil to movement even if sheet flow occurs. The closed canopy of leaves, the layer of litter and the mass of surface roots all serve to reduce the surface movement of soil to a minimum. The kinetic energy of the rain drops is adsorbed by the upper canopy, and the force of the drips from this canopy that may themselves have considerable energy, is cushioned by the lower canopy and the litter layer. The open condition of the surface layer beneath the litter promotes ready percolation into the soil (Lowdermilk, 1930).

In very heavy storms there may be surface run-off, even on upper slopes under mature forest, but the water usually runs clear due to the filtering action of the litter and fine surface roots, and the stability of the surface granules. (This is not always true of water flowing

over the concave valley slopes below the seepage line at the base of the upper convex slope. The water is often white with dispersed kaolin derived from subsurface flow.) Losses under forest have been recorded by Dabin (1959) from a small plot of 12–15% slope at Adiopodoumé, near Abidjan, Ivory Coast. Under a rainfall of 85 in. p.a., 0·4 ton per acre per year was eroded over 3 years. A similar plot of 7–8% slope under bare fallow lost 45 tons per acre per year. Such estimates obtained from small plots give only an approximate indication of the importance of erosion in modelling a landscape.

The considerable depth of soil developed on steep slopes under rainfalls exceeding 100 in. p.a. in tropical mountainous regions is itself a testimony to the efficacy of the forest in countering erosion.

In humid regions, provided there is a reasonable amount of available relief, the rate of downcutting on the one hand and the rate of creep on the other usually lead to the development of rolling topography with fairly steep slopes. By contrast, slopes in semi-arid regions are never steep except on definite rock faces, and boulder-controlled slopes. Steep slopes under the type of vegetation found in semi-arid regions are unstable, and if they arise they are rapidly worn down to the stable concave profile.

What then are the effects of cultivation in the forest region set against this broad background? The stripping of the cover promotes sheet flow. This will frequently occur on slopes which have the relatively steep forms adapted to creep. Conditions are therefore inherently unstable, but if cropping is limited in duration and plots are small and widely scattered, consequences may not be serious. Far more serious is the conversion of former forest vegetation to savanna. One has now a land form adapted to forest under a vegetation associated with a totally different form. It is in this region that the consequences of accelerated erosion are most apparent in terms of rate of removal of soil, particularly by gulleying. An excellent example of the catastrophic effects that may arise is provided by the well known gulleys near Agulu in south-eastern Nigeria (Grove, 1951*b*). As a result of overcropping, the forest cover was replaced by grasses, and gulleys were initiated at the foot of the convex hill slopes. The deep gulleys are now actively reducing the hill sides as their floor deepens towards that gentle concave profile which represents the stable land form under the changed conditions.

In land whose slopes have been developed under sub-humid conditions cultivation will not lead to such greatly accelerated removal of earth, since the land form is already adapted to sheet flow. Gulleys heading back from rivers are certainly a conspicuous feature of sub-humid landscapes. In many cases these are natural and should not be ascribed to accelerated erosion; in others, particularly in the drier savanna, they are due to overgrazing, not overcropping. The consequences of even small removals of surface soil

by sheet erosion in sub-humid areas may, however, be far more important than in humid areas, owing to the presence of hard pans close beneath the surface. This is further discussed in the next section.

Against this general long-term background we may now consider the effects of erosion during a single period of cropping.

When a forest fallow is cleared and burned nearly all the protective cover of vegetation and most of the litter are consumed, and the porous, granular mineral surface, which is mixed with finely divided partially decomposed litter and covered with a thin layer of ash, is bared to the shattering action of the heavy rain. The remains of the litter are rapidly decomposed, and the ash is washed into the soil, or with exceptionally heavy rain on a relatively impermeable soil it may be washed off the surface. Nevertheless the constitution of the soil is sufficiently stable to survive this onslaught for a few weeks until the early planted crops form a protective cover. The effects are mitigated by the fact that the plots cleared are small and are usually surrounded by undisturbed fallow so that run-off has little chance to accumulate; and by the fact that the stable surface granules of soil are little disturbed by cultivation. Gulleying is rare since the shallow surface roots of the forest trees are left in the ground, and effectively counter concentrated flow. Further erosion depends on the extent to which the soil is exposed during the subsequent cropping. The common practice of planting a mixture of perennial crops is very effective in maintaining a cover. Given small clearings, slopes not exceeding 50 per cent, and good crop cover, erosion on latosols under native practice is seldom serious. However, on steep slopes catastrophic erosion by slips may occur; for example, Kellogg (1949) writes of the Belgian Congo "because of the low activity of the clay and the stable aggregation, latosols are more permeable to water and less erosive than other soils, given comparable slopes and cover. But since the steeply sloping latosols are often among the most productive soils, steep hillsides of over 50 per cent slope, and up to nearly 100 per cent, are used for crops. Such steep slopes are subject to some soil movement by ordinary erosion, and by splash from raindrops, where exposed, but even more by movement in response to gravity and movement by slips".

Should the land be cleared again in the second year for another annual crop—a common practice in Asia—instead of leaving it under a semi-perennial crop, surface erosion may be more serious. Gonggrijp (1941) gives an account of an erosion experiment on volcanic soil at Tjiwidei in the per-humid mountains south of Bandoeng, Java. During the first year after clearing virgin forest and planting to rice there was little soil lost from either an unterraced or terraced catchment of 4·85 and 8·65 hectares respectively. However, in the second year the unterraced catchment lost 5·065 kg per sq. m.

(20 tons per acre approx.) and the terraced catchment lost half as much. These losses correspond to about 1/5 and 1/10 in. of the surface horizon—the most fertile layer. On more moderate slopes with close planted crops losses may not be so serious. Bonnet and Vidal (1958) have reported on erosion plots established at Seredou, in the forest region of Guinea, West Africa, with a rainfall of c. 100 in. p.a. and a slope of 25%. Here, land cleared from forest and planted to upland rice by native methods, which little disturb the top soil, lost 1·8 tons per acre in the first year, and less than 0·4 ton per acre in the second. Similarly at Kindia in middle Guinea, on a 'slightly ferrallitic' fine sandy clay on a 6% slope under a rainfall of 70 in. p.a., the loss of soil under three successive annual crops of *Digitarium exilis* (a close planted grass about 2 ft. high yielding small grains) averaged only 1·6 tons per acre per annum (Dugain and Fauck, 1959).

Another practice which accelerates erosion in forest is mounding or ridging the soil for root crops, such as yam, cassava and sweet potato, which respond to a loose soil. Waldock *et al* (1951) report that this practice is increasing in Sierra Leone, and it is common in Nigeria.

In the experiment at Seredou, mentioned above, two years of rice was followed by sweet potatoes on mounds or by cassava planted on the flat. There was a further loss of 1·8 tons per acre from the mounded plot but only a negligible loss from the undisturbed plot.

Since mounding and ridging are common practices in savanna, their serious consequences are discussed below.

For a number of reasons the effects of erosion under normal native cropping practices are far more noticeable in savanna than in forest. On land under gentle slopes typical of the sub-humid regions sheet and rill erosion is not serious while the land lies under a cover of grasses. It is true that these are burned every year and the surface of the soil lies bare when the early rains fall. Nevertheless where the land forms have been evolved under these conditions they have attained stability. The early storm water may be observed to flow over the surface in a smooth sheet carrying little sediment with it. The surface of the soil is usually a smooth expanse broken by tussocks of the bunch grasses and by numerous small termite mounds. These cause little interruption to the smooth-flowing water. Thus while the forest fallow disposes of storm water largely by maintaining the soil so open in the surface that the water is absorbed, the grass fallow in a graded sub-humid landscape plays the negative role of leaving the soil surface undisturbed so that water flows off as sheet flood and not as concentrated flow.

When the land is cleared, thorough hoeing is needed to rid it of grasses, and the smooth surface maintained under the fallow is disturbed. It is common to make the top soil into mounds or ridges,

which have the effect of providing good drainage and aeration, of concentrating the often thin layer of topsoil round the young plants, and of allowing large roots like yams to expand freely without distortion. The ridges often run up and down the slope, the better to dispose of surplus storm water and to improve drainage. Even when built on the contour, ridges may do more harm than good for they tend to pond at low points and eventually break through with the formation of a small gulley.

In the present setting the effects of the ensuing erosion may be considered to have short- and long-term aspects.

In the short-term the erosion leads to a loss of nutrients and humus from the top soil. We may examine the extent to which this leads to a loss of fertility in the two or three years of one cropping cycle. The actual losses of soil will of course vary widely with the details of each site, but some idea of their order of magnitude may be obtained from the average soil losses from land under wheat, corn and cotton at a large number of erosion experiment stations in the U.S.A. The averages were 24·66 tons per acre per annum (Bennett and Lowdermilk, 1938). This amounts to about a fifth of an inch of soil.

These data may be supplemented by recent results obtained in Africa. Though limited, these suggest that in spite of more intense rainfall erosion losses are certainly no greater than those recorded in the United States.

The amount of erosion on a variety of site conditions is being studied in Southern Rhodesia (Hudson, 1957) under rainfalls of around 40 in. p.a. In experiments extending over 3 years on soils ranging from a reddish brown clay to a light granitic 'sandveld' soil (35% coarse sand and 10% gravel), with slopes up to 8%, the maximum loss of soil in a year was 14·7 tons per acre. This occurred on the 8% slope of a sandveld soil under poor tobacco planted in rows which ran up and down the hill. In a later paper Hudson and Jackson (1959) stress the primary importance of a good cover in reducing erosion. Losses under 5 years continuous maize averaged 4·1 tons per acre per annum with a medium level of fertility and 10,000 plants per acre, and 1·2 tons per acre per annum with a high level of fertility and 15,000 plants per acre. In the first instance 40% of the ground was exposed to rain, and in the second only 10%. They also show that in all cases examined the eroded earth was richer in plant nutrients than the parent soil (presumably the plough layer). For organic carbon and nitrogen the enrichment ratio varied between 1·35 and 4·20 with a median value near 2.

At Mpwapwa, Central Tanganyika, (26 in. p.a.) Van Rensburg (1955) reports that unridged plots carrying sorghum on a 6·6% slope lost 22 tons per acre per annum over 8 years. In Madagascar the maximum loss recorded from a series of experiments was 6·2 tons per acre per annum—on a red ferrallitic soil of 8% slope under a

rotation of groundnuts, green manure, cassava and annual fodder, with a rainfall of 45 in. p.a. (Roche and Dubois, 1959).

Losses of this order, even allowing for the greater fertility of the eroded soil, and though serious in their cumulative effect, will not immediately deter farmers from further cropping.

It is in its long-term aspect that erosion in these regions is particularly serious. Vast tracts of nearly flat or gently sloping savanna lands are underlain at shallow depth by an iron-oxide cemented pan, or by an iron-oxide-enriched horizon which, though full of concretions, is friable in the natural condition, but becomes indurated when exposed to more intense desiccation on or near the surface. These areas, termed 'bovals' by French workers, occupy great tracts of savanna land and have been rendered quite useless for cultivation (see Prescott and Pendleton, 1952, for references).

In the savanna lands derived from moist forest, where slopes tend to be steeper as already described, short-term erosion following cultivation is certainly more severe. To arrive at some idea of the rate of increase in erosion with increasing slope it may be noted that Hudson and Jackson find that on the average, for plots of constant length, erosion $\propto$ slope$^{2\cdot02}$. This relation was determined for slopes from 3 to 6·5%. It is also important to note than on sandy soils under poor stands of maize—the conditions often found on peasant farms—erosion was found to increase even more rapidly with slope.

Some native peoples, forced into intensive cultivation of steep terrain by hostile tribes ranging the plains, have solved the problem by terracing the hillslopes. White (1941) for example, gives a description of the hill pagans of the Dikwa Emirate, Cameroons, who grow sorghum, beans and millets alternating with short fallows on the steep stone-walled hillsides, and succeed in supporting a population of 130 per square mile by this method. Greenland and Chancellor (1958) have mentioned other examples in Uganda and Ghana. The soils chosen seem usually to be developed from basic rocks. In Africa such practices are in the nature of curiosities, but they have links with America in the ancient Incaic terraces of Peru, still in use; and with south-east Asia where terracing for wet paddy-growing is widespread, but is also known for dry-land cropping where population pressure is severe, as on the island of Madura in Indonesia (Pelzer, 1948).

To summarize, the traditional system of shifting cultivation in the forest admirably protects the soil from erosion in spite of steep slopes and heavy rainfall. In savanna, erosion losses during a single period of cropping are usually slight because of the gentle slopes; and even on steeper slopes they are not sufficient to terminate the immediate cropping period. Repeated cycles of cropping and fallowing may however cause total ruin to savanna soils because they uncover subsoils rich in iron oxide, which if not indurated already, become so on exposure.

(e) The nutrient Status of the Soil

There are two ways in which the relation between declining yields and declining nutrient status in the soil has been studied: by fertilizer trials, and by soil analysis—the two are complementary, and the evidence they provide will be discussed in turn. Fertilizer trials are the surest way we have of identifying deficiencies of the major nutrients in the field, and of tracing the development of increasing deficiencies as cropping is continued. At the same time they tell us little about the concurrent changes in the chemical properties of the soil. Soil analysis is most useful for comparing the magnitude of the soil's nutrient reserves with losses by leaching and harvest, and in tracing the decline in reserves as the soil becomes exhausted by successive periods of cropping. It is, as yet, an imperfect instrument for predicting nutrient deficiencies and their effect on yields.

1. *The Evidence of Fertilizer Trials*

In the past fifteen years fertilizer trials have been carried out on the more important peasant crops in many parts of Africa. Their results may be formed into a fairly coherent pattern, if attention is paid not only to the morphology of the soils concerned, but also to the vegetation under which they were formed, and their cropping history. In the following account responses will be rated thus: very small, under 5%; small, 5–10%; moderate, 10–20%; large, 20–40%; and very large, over 40%.

(i) *Forest soils*

The general conclusions to be drawn from trials on these soils may be summarized as follows. Responses to nitrogen are very small where fallows have been long (say, 10 years or more), but in land more intensively cropped with only short fallows the responses become large. Responses to phosphates seem to depend as much on inherent properties of the soil as on its cropping history. Large responses have been obtained following a long fallow, and negligible responses following only a short fallow. When responses have been obtained they are smaller in the first year of cropping than in later years. Small or moderate responses to potash frequently occur on short-fallow land or land that has been cropped for a number of years. Responses to lime are usually small except in soils more acid than pH 5·0. Surprisingly, no great differences between the forest oxysols and the forest ochrosols have been revealed.

The trials on which these conclusions are based will be summarized briefly.

*Oxysols.* In Sierra Leone, experiments on peasant farms on upland soils showed large or very large responses to superphosphate on cereals, groundnuts and cassava (Piggott, 1954). In these soils the cropping period is 1–2 years and the fallow about 5 years (Waldock *et al.*, 1951). Responses were not as great in the first year after a bush

fallow as in the second and succeeding years. Only in a few isolated cases among many trials were responses to potash or nitrogen recorded.

In south-eastern Nigeria a large number of trials have been conducted on light, moderately to strongly acid soils derived in the main from Tertiary sediments, under rainfalls from about 70 to over 100 in. (Irving, 1954). The region is heavily populated, fallows are short, and the level of fertility of the soils is considerably below that of the soils under virgin forest. Yams, the main crop, showed large responses to sulphate of ammonia, no consistent responses to superphosphate and moderate responses to muriate of potash. The last effect was most marked on plots that did not have a bush fallow. The intercrops among the yams—maize, cassava and melon—behaved similarly to the yams: all showed large responses to sulphate of ammonia, no consistent responses to superphosphate, and small but consistent responses to muriate of potash.

On the very acid soils at Umuahia in this region (pH c. 4·1), maize grew poorly, but showed very large responses to small amounts of lime ($\frac{1}{2}$ ton per acre) which were sufficient to raise the pH to 5·0 (Doyne *et al.*, 1938). Further addition of lime had no beneficial effect, and on plots receiving 4 tons per acre, sufficient to raise the pH to 7·5, the maize showed symptoms of excess nitrogen unbalanced by other nutrients. Pot trials in which *Mucuna* leaves were added showed that no nitrate was produced over 3 weeks on the untreated soil, while the soil limed to pH 5·0 yielded 28 p.p.m. nitrate N, and that limed to pH 7·5 yielded 76 p.p.m. nitrate N.

The large responses to sulphate of ammonia on these overcropped permeable soils under very high rainfall tend to discount the suggestion, made for example by Tondeur (1956) in the Belgian Congo, that crops fail to respond to soluble fertilizers because their nutrients are too rapidly leached to have any beneficial effect. The more likely explanation is that the soils he studied contained adequate reserves of organic nitrogen (see p. 107).

At Cedara in Natal, on a yellow latosol of pH 5·0, one trial on maize showed very large responses to potash, but no or very small responses to nitrogen, phosphate and lime. One trial on millet showed very large responses to potash and small responses to phosphorus, lime, magnesium and trace elements (Orchard and Darby, 1956*a*).

In the Belgian Congo at the Bambesa Station and in the surrounding districts, on red and yellow lateritic soils with pH in the range 4·6–6·2, trials on cotton indicated small responses to dicalcium phosphate, ammonium nitrate and potassium sulphate (Laudelout, *et al.*, 1955). In the central Congo on soils of pH c. 4·5 addition of lime to plots receiving a complete mineral fertilizer gave moderate responses on maize and rice, groundnuts and soya. The effect was greater on the legumes (Culot and Meyer, 1959).

## TABLE 9

### Trends in Response to Fertilizers under a Continuous Crop Rotation

| | | Mature secondary forest | | | | | | | | Old established high-grass savanna | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Maize (6 trials) | | | | Cassava (6 trials) | | | | Cereals (4 trials) | | | Groundnuts (2 trials) | | | | Yams (2 trials) | | |
| Years after fallow | | 1–2 | 3–4 | 5–6 | 7–8 | 1–2 | 3–4 | 5–6 | 7–8 | 1–2 | 3–4 | 5–6 | 1–2 | 3–4 | 5–6 | 7–8 | 1–2 | 3–4 | |
| Mean Yield (lb./acre) | | 1180 | 510† | 560† | 790 | 13500 | 15800 | 11000 | 10500 | 1010 | 854 | 1561 | 969 | 774 | 713 | 656 | 9140 | 7210 | |
| Main Effects (Means as per cent of Mean Yield above) | N | 1 | −1 | −7* | 4 | −1 | 0 | −8 | 6 | 24** | 18** | 16** | 8* | −2 | 3 | −2 | 8 | −8 | |
| | P | 18** | 33** | 49** | 48** | 4 | 4 | 1 | −6 | 7 | 20** | 27** | 21** | 11* | 15** | 26** | −1 | 15* | |
| | K | 1 | 10* | 12** | 9* | 1 | 12** | 21* | 29** | 4 | −6 | −6 | −2 | −7 | −4 | 4 | 0 | 2 | |
| | L | 2 | 2 | 5 | 12** | 1 | 1 | 9 | 4 | 0 | 5 | 1 | 4 | 6 | 4 | 5 | −1 | 2 | |

Fertilizer treatments: n—1 cwt./acre sulphate of ammonia to each crop
p—1 cwt./acre single superphosphate (c.18% $P_2O_5$) to each crop
k—½ cwt./acre muriate of potash to each crop
l—5–10 cwt./acre lime (CaO) initially, and every 4 years (approx.) thereafter

*significant at P = 0·05
**significant at P = 0·01
†maize suffered severely from rust in these years.

*Ochrosols.* Along the southern forest borders of Ghana, on light soils derived from granite, numerous trials with maize on peasant farms showed large and consistent responses to sulphate of ammonia and moderate but erratic responses to superphosphate (Stephens, 1960*a*). The land was fairly intensively cropped, the cropping period being 2–3 years followed by 1–6 years of thicket fallow. The level of humus carbon in the 0–6-in. layer averaged 1·32%, and nitrogen 0·165%.

Very similar results have been obtained in large numbers of trials on peasant farms in the Western Region of Nigeria, on light soils derived from granite and Tertiary sands. Yams showed moderate responses to sulphate of ammonia, and small responses to superphosphate, while maize showed small responses to sulphate of ammonia and superphosphate, (Kowal, priv. comm.). Greater responses were obtained on sites cropped over 4 years. Upland rice gave small responses to sulphate of ammonia (reduced by lodging) and moderate responses to superphosphate. All these farms were fairly intensively cropped –about 3 years of cropping alternating with 3–4 years of woody fallow.

The way in which deficiencies increase if, contrary to native practice, cropping is continued for many years, is illustrated by the results of 6 trials in the forest zone of Ghana maintained under a continuous rotation of maize and cassava for 8 years (see Table 9) (Nye and Stephens, 1960). Two of these trials were on oxysols and four on ochrosols, but no clear differences were observed. All trials were started from secondary forest some 10 years old. No shortage of nitrogen developed during the whole period. Phosphorus gave large and increasing responses on maize, but had little effect on the root crop—cassava. The development of an increasing response to potassium after the third year was particularly interesting, cassava with its high potassium requirement proving far more sensitive than maize. Small responses to lime developed in later years.

In the permanent manurial trial at the Imperial College of Tropical Agriculture, Trinidad, a total of 28 crops were grown between 1931 and 1945 (Hardy and Evans, 1945). There were small responses to nitrogen, none to phosphate, large responses to potash and none to lime. Because of the unsystematic sequence of cropping it is not possible to discern trends with time in this trial.

(ii) *Savanna soils*

Trials on peasant crops in savanna areas have been more numerous than in forest. The broad conclusions are fairly clear. Moderate or large responses to nitrogen are usual on most savanna soils, even those that are infrequently cropped. The response in fact is particularly marked in the first year after clearing from a long high-grass fallow. Though it might be expected that responses would be greater the more intensively the land was cropped there is little evidence that this is so, possibly because of a parallel shortage of

phosphorus. In addition, on the poor soils of the drier regions shortage of water may limit the nitrogen effect.

Small to large responses to phosphorus are usual. The response is partly governed by inherent soil character, but tends to be small on newly cleared land and to increase with cropping.

Responses to potash, lime and micronutrients are rare under peasant-farming practices.

The trials on which these conclusions are based will be briefly reviewed, starting with those on land which has been little cropped. The general trends of the responses are illustrated by results of trials in Ghana maintained under a continuous rotation for nine years (see Table 9). The land was cleared from old established high-grass savanna dominated by the Andropogoneae. On cereals, initial responses to nitrogen were large and later moderate, while responses to phosphorus increased steadily. There were no responses to potassium and only small responses to lime over the period.

Further trials showing the acute deficiency of nitrogen in the first year on land cleared from high-grass (Andropogoneae) fallow have been reported by Nye (1950) on several sites in Ghana, and Greenwood (1951) at Kontagora in Nigeria. Anderson (1957) mentions the large response of maize and sorghum to nitrogen on Nachingwea sandy loam, Tanganyika, with high C/N (c. 18) in contrast to the slight responses on the Kongwa red earths with low C/N (c.11), where, however, water may be the limiting factor. Rounce and Milne (1936) have noted the poor growth of grain crops, apparently due to nitrogen deficiency, on newly opened land in the Kasulu district, near Lake Tanganyika, and Hosking (1937) and Small (1937) have made similar observations in Eastern Uganda and Nyasaland; though not specifically described, the vegetation in each instance appears to be high-grass (Andropogoneae) savanna.

This acute deficiency of available nitrogen following a long fallow is confined so far as we know to the fallows of the Andropogoneae. Comparable effects have not been reported on crops following a long fallow of *Pennisetum purpureum* or *Panicum maximum*. The deficiency of nitrogen in the first year on land taken from high-grass fallow is reflected in the practice over many parts of Africa of planting yams, cotton or tobacco as opening crops rather than cereals.

Responses to phosphorus following a long-term fallow are usually small, though they build up if cropping is prolonged (Nye, 1957, Stephens, 1960*b*).

In more exhausted savanna land where fallows are of short duration very large numbers of trials with NPK on a range of food crops have now been carried out in west, east and south Central Africa. Greene (1954) has presented a review of them.

The broad conclusions of all this work are remarkably uniform. Cereals, yams and cotton usually show moderate or large responses

to nitrogen. The same crops together with groundnuts usually show small to large responses to superphosphate.

The lack of response to potash under peasant farming in the savanna areas, even on intensively cropped soils, is remarkable. Numbers of long-term trials under a continuous rotation of crops have been conducted on impoverished savanna soils, in Ghana for 9 years and in Northern Nigeria for 7 years (Obi, 1957). In none of these trials has potash given a consistent response. The only responses mentioned from East Africa are on the coral limestone soils of Zanzibar (Calton *et al.*, 1955), in the coastal belt of Tanganyika (Doughty, 1953) and on wheat and tobacco in the Tanganyika Southern Highlands (Gunn, 1953). The first two groups of soils were presumably developed under moist coastal forest, and their shortage of potassium may be inherited from this period.

Responses to lime on native food crops in the savanna zone are small. In East Africa responses on cereals when the soil has a pH over 5·0 are rare (Keen and Duthie, 1953). Very acid savanna soils where more frequent responses might be expected are uncommon. In Ghana where savanna topsoils have a pH of 6·0–6·5, groundnuts, cereals and yams all show small responses to lime (Nye and Stephens, 1960). On groundnuts the effect is on growth, and not shelling percentage, as in Ca-deficient areas in the south-eastern U.S.A.

In these remote savanna areas far from industrial districts and in most cases far from the sea, a deficiency of sulphur might be expected. The deficiency will be accentuated by the loss to the atmosphere that occurs on annual burning of the grasses (Chenery, 1958). Sulphur deficiency on groundnuts has indeed been established over wide areas in Northern Nigeria (Greenwood, 1954) and Ghana (Nye and Stephens, 1960), and on clover and lucerne at Kitale, Kenya (Chenery, 1958). Sulphur deficiency in West Africa is most acute after a high-grass (Andropogoneae) fallow. No responses to sulphur on cereals have been obtained.

The possibility of deficiencies of micronutrients in the ancient continental soils of the tropics has tempted many a reasoned speculation (e.g. Greene, 1954). Micronutrient deficiencies on perennial export crops have been established in many parts (see Schutte, 1955, for a review of work in Africa, and Chenery, 1958, for a more recent review of work in East Africa), but deficiencies have rarely been demonstrated under the conditions of native subsistence farming, even on inherently poor soils that are intensively cropped.

It is true that spectacular deficiencies of molybdenum, copper and zinc have been demonstrated in a variety of plants growing in pots on a soil from the Yundum Experimental Farm, Gambia (Webb, 1954), but these results have not been confirmed in the field. (Report on Field Trial Results 1958, communicated by Director of Agriculture, Gambia.)

In an extensive series of factorial trials in Ghana cereals and groundnuts failed to respond to manganese, boron, copper, zinc,

iron or magnesium. In 19 trials on groundnuts, however, sodium molybdate increased the yields by 12% (Stephens, 1959). In Senegal groundnuts showed small responses to copper, magnesium and molybdenum, but not to iron, manganese or boron (I.R.H.O., 1952).

2. *The Evidence of Soil Analyses*

The value of soil analysis as an index of fertility decline is limited because of difficulties in interpretation. The conventional measurements, such as total N and exchangeable cations, tell us about the amounts of nutrients present, but not directly about their 'availability' on which the immediate growth of crops depends. They are in fact measurements of 'capacity' not 'potential' (see Black, 1957 for references on this subject). Nevertheless as 'capacity' measurements they do help considerably in interpreting the processes of soil exhaustion indicated by declining yields and increasing responses to fertilizers. In addition they can, rightly understood, give a guide to nutrient 'potentials'. For example, within a range of soil, climate and crop there is a relation between the total nitrogen in the soil and its availability. Similarly the percentage of potassium in the exchange complex is related to the availability of potassium.

It is convenient here to consider first the decline in soil humus during the cropping period. The decline in the availability of nutrients in the soil will be considered subsequently.

(i) *Changes in the quantity of humus*

Much has been written about the destructive effects of cultivation on the reserves of humus in tropical soils. Beirnaert (1941), in a widely quoted example, published an account of his estimates of the "Influence de la culture sur les réserves en humus et en azote des terres équatoriales" and arrived at the startling conclusion that for the first year or two after clearing from forest about one ton of humus and 5 tons of old roots were oxidized per hectare each *month*. The rate of loss of humus was over 12% of the total per annum. These estimates were based on a comparison of adjacent areas of forest and clean-weeded bare fallow, not on measurements of the successive changes taking place on one area. As Beirnaert himself admits, it is quite possible that the two areas did not have the same initial humus contents. The quantity of roots estimated is also exceptionally high, about four times the similar amounts found by Bartholomew *et al.* (1953) at Yangambi under 18-year-old forest and by Greenland and Kowal (1960) under 40-year-old forest in Ghana. Beirnaert does not consider the estimate of root weight in any detail nor are sampling techniques described. Furthermore the rate of decline of humus is likely to be much greater in a bare fallow than when the land is cropped.

Reports by agriculturists and others frequently refer to the visible decline of humus on clearing, and the rapid oxidation that arises from exposure of the soil and consequent higher soil temperatures.

The visible change, which is most apparent in forest areas, is at least in part due to the mixing of highly humic topsoil with subsurface soil during cultivation. The humus is buried, not oxidized (cf. Table 10), and may still contribute importantly to soil fertility.

Another reason why a false impression of excessive oxidation rates of soil humus has arisen is the publication of exaggerated estimates of litter return under forest. Thus Vageler (1933) states that "The yearly production of fresh organic matter in the primaeval forest approaches one hundred tons per acre on a cautious estimate," a "cautious estimate" unfortunately resurrected by Tempany and Grist (1958), who state (p. 41) "Yearly production of organic matter is great, possibly exceeding 100 tons per acre." Actual measurements of litter fall in tropical forests (Table 5) show that the average is about 4 tons oven-dry weight per acre per annum. Root additions are probably about half the litter fall. The total annual production of organic matter is not likely to exceed this by very much, as the total quantity of vegetation in 40-year-old forest is only about 150 tons, corresponding to a net rate of increase of 3 to 4 tons per acre. An estimate of organic-matter additions more than ten times too great implies an estimate of the oxidation rate of organic matter and of the humus formed from it that is correspondingly exaggerated. Tempany and Grist (p. 110) can thus suggest that "In the tropics the rate of disappearance of organic matter is so rapid that it is doubtful whether humus (as it is understood in temperate countries) is formed." Such a statement gives a very erroneous impression. There is ample evidence to show that humus in the tropics is often present in considerable amounts and has properties just as beneficial as humus in temperate soils (cf. estimates of exchange capacity of the humus fraction, quoted on p. 57, the many publications referring to the nitrogen release by mineralization of such humus, and the similarity of the microbial population of these soils and temperate-zone soils). Furthermore, actual measurements of the rate of decline of humus are available from a variety of sources, and all these show that while it is larger than in soils of the temperate zone, it is not so large that loss of humus necessarily becomes a serious problem, even over a cropping period of ten or more years. In soils of very low humus content, such as occur in the drier savanna areas, a high rate of decomposition is even desirable, in order to release sufficient nitrogen for crops (see below).

Most data on the rate of decline come from measurements of soil changes occurring under trials conducted at research stations. These data are collected in Table 10. The rate of humus decline, $k_c$ has been calculated from the changes in soil carbon, assuming that there is a simple exponential decrease following the equation $\frac{dC}{dt} = -k_c C$, where $k_c$ is the decomposition constant and C the

## TABLE 10

### Changes in the Chemical Constitution of Tropical Soils under Continuous Cropping

| No. | Place | Rainfall in. p.a. | Cropping | Years | Depth in. | pH | C% | N% | Av. P p.p.m. | Exchangeable K | Exchangeable Ca | Exchangeable Mg | T.E.C. (Meq. per 100 g.) | C.E.C. | Losses, lb. per acre kc | N | P | K | Ca | Mg | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Aiyinasi, Ghana Evergreen forest | c.82 | Maize, cassava rotation | 0 | 0–6 | 6·0 | 2·19 | 0·164 | 16·0 | 0·22 | 4·62 | | | 10·0 | | | | | | | After clearing from old secondary forest. |
| | | | | 8 | 0–6 | 5·0 | 1·50 | 0·128 | 3·7 | 0·26 | 2·05 | | | 9·3 | | | | | | | |
| | | | | 0 | 6–12 | 5·0 | 1·28 | 0·103 | 6·0 | 0·16 | 1·37 | | | 7·2 | *0–12* | | | | | | |
| | | | | 8 | 6–12 | 4·8 | 1·02 | 0·089 | 2·6 | 0·25 | 1·18 | | | 8·6 | 4·0 | 1000 | 31 | Inc. | 1100 | | |
| 2 | Arena forest reserve, Trinidad Evergreen forest | | | 0 | 0–6 | | 1·57 | 0·06 | | | | | | | | | | | | | After clearing from high forest. |
| | | | | 2 | 0–6 | | 1·15 | 0·05 | | | | | | | | | | | | | |
| | | | | 0 | 6–12 | | 0·81 | 0·03 | | | | | | | *0–12* | | | | | | |
| | | | | 2 | 6–12 | | 0·83 | 0·04 | | | | | | | 9·0 | | | | | | |
| | | | | 0 | 12–24 | | 0·53 | 0·02 | | | | | | | *0–24* | | | | | | |
| | | | | 2 | 12–24 | | 0·59 | 0·03 | | | | | | | 3·9 | | | | | | |
| 3 | Trinidad Moist, semi-deciduous forest | | Varied, with 2 or 3 crops per yr. including legumes | 0 | 0–6 | 6·1 | 1·02 | 0·13 | 16·8 | ('Available') 0·085 | | | | | | | | | | | Land probably cleared from young secondary forest. |
| | | | | 6 | 0–6 | 6·7 | 0·84 | 0·11 | 10·4 | 0·175 (0·075?) | | | | | *0–6* | | | | | | |
| | | | | 12 | 0–6 | 6·9 | 0·80 | 0·11 | 9·9 | 0·066 | | | | | 2·6 | | | | | | |
| | | | | | | | | | | | | | | | *0–6* | | | | | | |
| | | | | | | | | | | | | | | | 1·8 | 400 | 13 | (15) | | | |
| 4 | Kwadaso and Mampong, Ghana Moist semi-deciduous forest | 55–60 | Maize, cassava rotation | 0 | 0–6 | 5·7 | 2·12 | 0·191 | | | | | | | | | | | | | Means of composite samples taken from 5 rotation fertilizer experiments. |
| | | | | 6 | 0–6 | 6·0 | 1·63 | 0·148 | | | | | | | | | | | | | |
| | | | | 0 | 6–12 | 5·2 | 0·80 | 0·077 | | | | | | | | | | | | | |
| | | | | 6 | 6–12 | 5·7 | 0·92 | 0·086 | | | | | | | *0–12* | | | | | | |
| | | | | | | | | | | | | | | | 2·3 | 680 | | | | | |
| 5 | Bambesa, Belgian Congo Moist semi-deciduous forest | c.70 | Maize, cotton, groundnuts, cassava, bananas | 0 | 0–4 | 5·7 | 1·95 | | | | | | 2·7 | | | | | | | | Increases in C and exch. cations probably associated with inclusion of bananas in rotation. |
| | | | | 3 | 0–4 | 6·65 | 2·9 | | | | | | 4·2 | | Increase | | | | | | |
| | | | Bananas, groundnuts, cassava, maize and cotton | 0 | 0–4 | 5·78 | 2·0 | | | | | | 3·0 | | | | | | | | |
| | | | | 3 | 0–4 | 5·78 | 2·2 | | | | | | 3·5 | | Increase | | | | | | |
| 6 | Benin, Nigeria Moist semi-deciduous forest | 72 | | 1 | 0–6 | 5·8 | 0·86 | 0·080 | | 0·125 | 3·28 | 0·85 | 3·6 | 5·0 | | | | | | | Established by clearing and burning 50 yr. old forest. Intercropping treatment of oil-palm establishment experiment: Palms commenced to bear at 5 years. After 11 years yields of intercrops became so low intercropping discontinued. |
| | | | | 5 | 0–6 | 6·1 | 0·95 | 0·080 | | 0·119 | 3·66 | 0·70 | 3·7 | 5·1 | | | | | | | |
| | | | | 11 | 0–6 | 5·7 | 0·75 | 0·066 | | 0·084 | 3·12 | 0·55 | 3·4 | 5·0 | *0–6* | 280 | | 34 | 64 | 96 | |
| | | | | | | | | | | | | | | | 1·3 | | | | | | |
| | | | | 1 | 6–18 | 4·7 | 0·44 | 0·037 | | 0·100 | 1·14 | | 1·7 | 3·5 | | | | | | | |
| | | | | 11 | 6–18 | 5·6 | 0·48 | 0·047 | | 0·082 | 1·90 | | 2·3 | 4·2 | *0–18* | Inc. | | 63 | Inc. | | |
| | | | | | | | | | | | | | | | 0·2 | (120) | | | (540) | | |

| | | | | Yr. | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7 | Idaban Nigeria Moist semi-deciduous forest —savanna margin | 48 | 1. Maize, popondo | 0 | Depth not | 6·4 | 0·54 | 0·048 | | | | | 4·1 | | | | | Established on land previously cropped. After 5 years continued on ½ plots. |
| | | | 2. Yams, popondo | 5 | stated probably | 6·4 | 0·47 | 0·041 | | | | | 3·8 | *0–6?* 2·8 | | | | |
| | | | 3. Maize, cotton | 5 | 0–6 | 6·4 | 0·48 | 0·042 | | | | | 4·0 | | | | | |
| | | | 4. Maize, mucuna maize, and popondo Repeated | 11 | | 6·3 | 0·38 | 0·033 | | | | | 3·3 | *0–6?* 3·1 | 300 | | | |
| 8 | Séfa, Senegal Guinea savanna woodland | 52 | Groundnuts, cereals | 0 | 0–6 | 6·4 | 0·75 | 0·15 | 0·22 | 2·2 | | | | | | | | Fresh cleared from old savanna woodland. *Mechanized* cultivation. Approximate data only. |
| | | | | 6 | 0–6 | 5·5 | 0·50 | 0·10 | 0·12 | 1·2 | | | | *0–6* 6·8 | 1000 | 80 | 400 | |
| 9 | Yambio, Sudan | 57 | Rotations of cotton, maize, eleusine, groundnuts | −6 | 0–6 | 6·7 | 1·43 | 0·119 | | 4·7 | | | | | | | | After 6 years fallow. |
| | | | | +2–4 | 0–6 | 6·6 | 1·34 | 0·112 | | 5·0 | | | | | | | | After 2 yrs. crop and 4 yrs. fallow. |
| | Guinea Savanna | | | +4–2 | 0–6 | 6·5 | 1·38 | 0·109 | | 4·7 | | | | | | | | After 4 yrs. crop and 2 yrs. fallow. |
| | | | | +6 | 0–6 | 6·5 | 1·32 | 0·110 | | 4·4 | | | | *0–6* <1·4 | | | | After 6 yrs. crop. |
| 10 | Ghana | 45–55 | Various rotations of yams, cereals, groundnuts | 0 | 0–6 | 6·2 | 0·36 | 0·034 | | | | | | | | | | Means of 14 trials at 6 stations. 6″–12″ means of samples of 6 of above 14 trials. |
| | | | | 6 | 0–6 | 5·7 | 0·28 | 0·025 | | | | | | | | | | |
| | Guinea Savanna | | | 0 | 6–12 | 5·7 | 0·22 | 0·024 | | | | | | *0–12* | | | | |
| | | | | 6 | 6–12 | 5·6 | 0·17 | 0·018 | | | | | | 4·2 | 300 | | | |
| 11 | Boulel, Senegal Open dry forest | 36 | Millet, groundnuts, | 0 | 4–8 | 6·5 | 0·31 | 0·32 | 0·06 | 1·08 | 0·69 | 1·90 | | Increase | | | | Mechanized cultivation after clearing from old open dry forest. Mineral fertilizers applied. Exchangeable cations show erratic fluctuations. |
| | | | | 8 | 4–8 | 5·8 | 0·33 | 0·31 | 0·03 | 1·00 | 0·31 | 1·41 | | | | | | |
| | | | green manure, groundnuts | 0 | 14–18 | 6·1 | 0·19 | | 0·03 | 0·72 | | 1·36 | | | | | | |
| | | | | 8 | 14–18 | 5·5 | 0·19 | | 0·02 | 0·73 | | 1·16 | | | | | | |
| | | | | 0 | 28–32 | 6·3 | 0·20 | | 0·03 | 1·22 | | 2·16 | | | | | | |
| | | | | 8 | 28–32 | 5·5 | 0·18 | | 0·03 | 0·90 | | 1·79 | | | | | | |

References: 1. Stephens (unpublished) 2. Brooks, 1937 3. Hardy & Evans, 1945 4. Stephens (unpublished) 5. du Bois, 1957 6. Kowal & Tinker, 1959 7. Moor Plantation Nigeria Annual Report, 1948 (unpublished) 8. Fauck, 1956 9. Anthony & Willimott, 1956 10. Stephens (unpublished) 11. Bouyer, 1959

humus-carbon content of the soil after t years of cultivation. For the initial years of cultivation this is a very close approximation. Thereafter the rate apparently decreases, and the carbon content of the soil does not in fact tend to zero with increasing time of cultivation, but to some equilibrium level, dependent on the soil type and crops grown. The effect of this may be seen in example 3, Table 10, where the rate of loss calculated for the first 6 years is 2·6% per annum, whereas that for 12 years is 1·8%. Henin and Dupuis (1945) have discussed this point fully in connection with temperate soils.

The examples of Table 10 are all taken from experiments conducted at research centres. Excepting, for the moment, examples 5 & 6, the rates of decline in such experiments are likely to be greater than those occurring under native practice, for the following reasons: (1) in the examples from forest the soil is more thoroughly disturbed by cultivation, even when done by hand, than it usually is by the native farmer, and aeration and oxidation are thereby enhanced; (2) weeding is done more thoroughly, and the return of organic matter as weed residues is thereby reduced; (3) all trees are completely removed from the site, or at least killed, whereas under native practice some are left, their litter and shade helping to maintain soil humus; (4) roots which might otherwise contribute to soil humus are often removed. On the other hand, closer planting of crops and higher yields will give greater returns from crop residues.

The most important difference may be the leaving of shade trees or the interplanting of the food crops with tree crops or bananas. Thus in example 5 it is seen that at Bambesa in the Congo organic matter actually increased in 3 years of cropping, and continued to increase if cropping was continued, if bananas were included in the rotation (du Bois, 1957). Presumably the important contribution to the soil humus comes from banana leaves which are shed during growth and form an effective mulch. Bananas or plantains very commonly form the last crop planted under native cultivation throughout the forest area. In the intercropping experiment with oil palms (example 6) the rate of humus decline was found to be very low (Kowal and Tinker, 1959). This experiment was designed to test the effects of different inter-row treatments on the establishment and yield of oil palms. Of the various treatments, intercropping leads to the highest returns of oil-palm fruit (Sparnaaij, 1957). While the rate of loss of humus under this treatment is low compared with cropping not accompanied by tree crops, it was the largest found under any of the inter-row treatments tried. Interplanted legumes and frequently slashed or annually slashed natural regrowth gave rise to an increase of humus, as might be expected from what has been said in Part I.

There have been very few studies made of the changes in the chemical composition of soils actually under shifting cultivation. Two areas in Ceylon were examined at successive intervals by Joachim and Kandiah (1948), and in the same paper the authors

## TABLE 11

### Changes in the Chemical Constitution of Soils under Shifting Cultivation

| No. | Place | Rainfall in. p.a. | Depth in. | pH | C% | N% | Av. P p.p.m. | Exchangeable K | Exchangeable Ca | Exchangeable Mg | Exchangeable T.E.C. | C.E.C. | Total losses lb. per acre kc | Total losses lb. per acre N | Total losses lb. per acre P | Total losses lb. per acre K | Total losses lb. per acre Ca | Total losses lb. per acre Mg | No. of samples | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Meqs. per 100 g. | | | | | | | | | | | | |
| 1 | Eriyagama, Ceylon | c.60 | 0–6 | 7·4 | 2·55 | 0·218 | 19·0 | | | | 25·6 | | | | | | | | | After burning jungle |
| | | | 0–6 | 7·6 | 2·27 | 0·186 | 9·2 | | | | 20·2 | | | | | | | | | Same area after 1st crop |
| | | | 0–6 | 7·7 | 2·15 | 0·187 | 13·0 | | | | 20·4 | | 8·5 | 640 | 20 | | | | 'several' | Same area after 2nd crop |
| | Rambawa, Ceylon | c.60 | 0–6 | 7·4 | 1·32 | 0·117 | 22·0 | | | | 11·1 | | | | | | | | | After burning jungle |
| | | | 0–6 | 7·4 | 1·23 | 0·116 | 20·0 | | | | 10·2 | | | | | | | | 'several' | Same area after 1st crop |
| | | | 0–6 | 7·4 | 1·13 | 0·104 | 19·0 | | | | 10·3 | | 7·8 | 260 | 6 | | | | | Same area after 2nd crop |
| 2 | Polochic valley, Guatemala | 135 | 0–2 | 5·4 | 19·8 | 1·08 | | 0·69 | 23·6 | 6·2 | 37·2 | 88·8 | | | | | | | Means of 60 samples from 6 "fields" | Forest, possibly virgin |
| | | | 2–8 | 5·4 | 8·9 | 0·505 | | 0·22 | 11·7 | 3·2 | 16·7 | 44·5 | | | | | | | | |
| | | | 8–16 | 5·7 | 3·4 | 0·296 | | 0·12 | 7·5 | 2·5 | 11·2 | 34·6 | | | | | | | | |
| (N.B. Not typical upper slope latosol. Soil of very low density, very high organic matter, possibly Ando type.) | | | 0–2 | 5·9 | 9·6 | 0·779 | | 0·86 | 20·9 | 5·5 | 29·2 | 62·4 | | | | | | | Means of 60 samples from 6 fields adjacent to 6 forest "fields". | Cleared land in middle of first cropping season. |
| | | | 2–8 | 5·5 | 7·4 | 0·391 | | 0·32 | 9·9 | 3·2 | 12·7 | 39·3 | | | | | | | | |
| | | | 8–16 | 5·8 | 2·4 | 0·219 | | 0·19 | 9·6 | 3·4 | 11·2 | 35·4 | | | | | | | | |

References: 1. Joachim and Kandiah, 1948
2. Popenoe, 1957

give comparisons for other parts of Ceylon of adjacent areas under differing stages of shifting cultivation. Only the data for the successively sampled areas are given in Table 11, as the data for the other areas show large random errors. The rate of humus loss is apparently much higher than on the station experiments. No details are given in the paper of the crops grown or of the soil treatments, nor are sampling techniques described in any detail. Furthermore samples were only taken to 6 inches. Examples 2, 4 and 6 of Table 10 show that losses in the top 6 inches of soil may be partly offset by increases in the 6–12 in. layer. In spite of the apparent rapid decline the humus content of the soil at the end of the cropping period is by no means so low as to make cropping difficult.

Popenoe (1957) has compared the soil composition of areas of adjacent land at different stages in the shifting-cultivation cycle, in the Polochic valley in Guatemala (Table 11, example 2). The soils in this area are derived from 'limestone and metamorphosed material', and have been enriched by deposits of volcanic ash. The humus levels are very high and the soil densities exceptionally low. They are not therefore latosols, but appear to be soils of the 'Ando' group. As soil densities are only quoted for the 2–4 in. layer it is not possible to convert the figures to pounds per acre, nor to calculate the rate of carbon loss, as the relative values to be given to the quantities in the different soil horizons are not known. Cropping sharply increases the density of the 2–4 in. layer, thus apparently decreasing the humus and nutrients in this top soil, sampled to a fixed depth. This example does, however, show that under shifting cultivation land may be abandoned even when the soil contains as much as 10% carbon in the surface soil.

(ii) *The relation between humus level and cropping intensity*

Many reports show that humus in areas of soils cultivated for many years by shifting cultivation is still relatively high, e.g. Hardon (1936) for Sumatra, Killian (1942) for the Ivory Coast, Coulter (1950) for Malaya, Reed (1951) for Liberia, Endredy and Montgomery (1954) for Ghana, Birch and Friend (1956) for East Africa, Pernet (1954) for Madagascar. Only in savanna areas subjected to repeated grass burning are very low levels of soil humus found (cf. the data for northern Ghana, Table 3, example 10; Ballantyne, 1957 and Dabin, 1953). The low levels here are due primarily to the slow build-up of humus under the burnt grass fallow, so that the losses of humus in each period of cultivation are virtually additive.*

* There are no reports of the humus changes which take place if soils in these areas are left under unburnt grass for a number of years, but Edwards (1942) observed that the loss on ignition and cation-exchange capacity of the soil under unburnt plots of *Themeda triandra* grassland in the Kenya Highlands increased compared with burnt plots. On a similar experiment in South Africa Cook (1939) observed that the total nitrogen in the 0–1·5-in. layer fell from 0·21% to 0·12% after 7 years of annual burning, whereas on the unburnt plot it remained relatively constant. Both these experiments were with soils of higher humus contents than those referred to here. It is probable that the increases in soils of low initial humus content would be relatively larger than those reported.

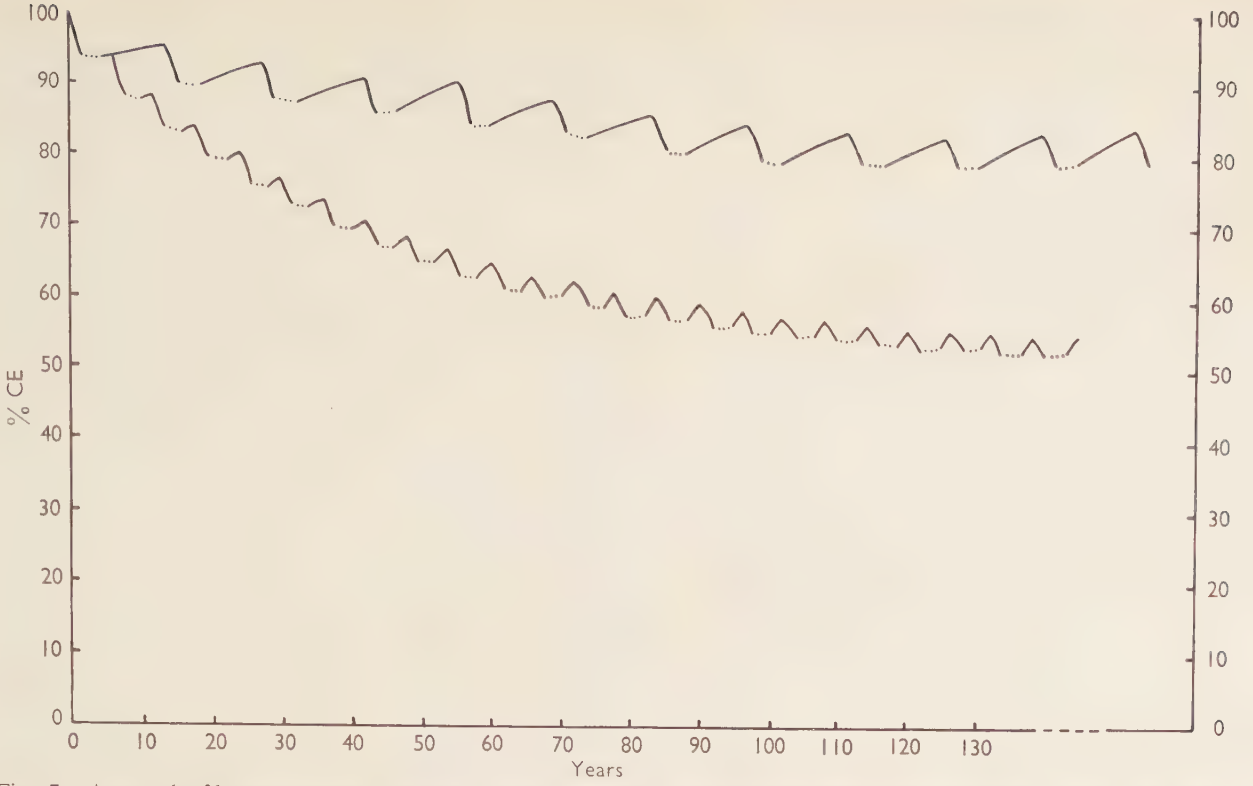


Fig. 7. Approach of humus carbon in top foot of virgin forest soil to equilibrium under shifting cultivation, with 2 year crop. 12 year fallow cycle (upper curve) and 2 year crop. 4 year fallow cycle (lower curve). Both curves have been calculated for conditions where $k_f = k_c = 3\%$ and allowing a 2 year lag period (broken line) for the fallow to re-establish itself. No allowance is made for erosion losses.

Because of the low level of humus the farmer is forced to ridge or mound his soil to get maximum aeration and maximum nitrogen mineralization, with the consequent further decline in humus. Thus a vicious circle is established, one that has led to the virtually complete exhaustion of humus reserves in some areas.

It is possible to relate the level of humus that will eventually be established at any cropping intensity to the 'virgin' level that is attained after a long rest under the fallow ($C_E$). The approach of a virgin forest soil to the 'steady' level under high and low cropping intensity is illustrated in fig. 7. The rate of increase in humus carbon during the fallow period is given by

$$I = A - k_f C$$ (see p. 51)

so that in any relatively short fallow period of $T_f$ years,

$$I = \frac{\triangle C_f}{T_f} = A - k_f C$$

and substituting $k_f C_E$ for A,

$$\triangle C_f = k_f(C_E - C)T_f.$$

The decrease in humus carbon during the cropping period, when additions to the humus carbon may be assumed to be negligible, is given by

$$\triangle C_c = - k_c C T_c$$

where $k_c$ is the decomposition constant for the cropping period and $T_c$ the length of the cropping period. Therefore the net change in one cycle of fallow and crop is

$$\triangle C = k_f T_f C_E - (k_f T_f + k_c T_c)C$$

The level of humus eventually established will be such that there is no net change in the humus carbon, i.e.

$$\frac{C}{C_E} = \frac{k_f T_f}{k_f T_f + k_c T_c}$$

Two examples of the application of this equation may be given. When a forest soil is cropped with little disturbance of the surface and good shade it is likely that the rates of decomposition of humus during the cropping and fallowing periods will be similar. $k_f$ has in fact been estimated independently to lie between 2 and 5% (Greenland

and Nye, 1959), and $k_c$, shown by results in Table 10, is about 3%. If $k_f = k_c$, then

$$\frac{C}{C_E} = \frac{T_f}{T_f + T_c},$$

a very simple relationship. As mentioned on p. 47 Reed (1951) found the level of humus in large numbers of Liberian forest soils cropped for 2 years and fallowed for about 10 to be 75% of the virgin level. The level that would be calculated is 80% (allowing 2 years for fallow establishment).

When a savanna soil is cropped the rate of decomposition of humus exceeds that under the grass. $k_f$ has been estimated to lie between 0·5 and 1·2%, and $k_c$ from Table 10 may be 4%. If, for example, $k_f = 1$,

$$\frac{C}{C_E} = \frac{T_f}{T_f + 4\,T_c}$$

Thus equal periods of crop and fallow may be expected eventually to reduce the humus level to only a fraction of the level that would be attained if the fallow was prolonged.

We have so far considered only the changes of humus as measured by changes in the organic-carbon content of the soil. It is possible, however, that the change in humus quality is more important than the change in quantity. The limitations of methods for determining humus quality have been discussed in Part I (pp. 57–62), and it was suggested there that the best measures of quality were obtained from measurements of the soil properties associated with humus. The effect of humus losses on the physical constitution of the soil have already been considered. Changes in the rate at which the humus is mineralized will now be considered in relation to soil-nitrogen changes. The effect of changes in the humus on the cation-holding power of the soil will be considered subsequently, and in section (f) the relationship of humus losses to the microbiological activity in the soil, will be outlined briefly.

(iii) *Changes in the availability of soil nitrogen*

The store of organic nitrogen in the soil only becomes available to crops when it is converted into the mineral form. The amount becoming available in any one period depends on the activity of the micro-organisms bringing about the decomposition and the amount of organic nitrogen in the soil. The activity of the micro-organisms bringing about the decomposition of soil humus and organic matter added to the soil is determined by a variety of factors, such as temperature, moisture content, aeration, vegetation type, pH and the chemical nature of the humus or organic matter.

The relative importance of these factors varies considerably between the oxysols of the moist evergreen-forest zone and the ochrosols of the moist semi-deciduous forest and also between the forest and savanna soils. The evidence regarding the mineralization of nitrogen in each of these areas will therefore be considered separately. We learn most about the mineralization of soil nitrogen from studies of soil-nitrate levels, but data relating to nitrogen mineralized during incubation tests and the density of nitrifying bacteria in the soil also provide us with useful information.

### Moist evergreen forest

No determinations of the level of nitrate nitrogen throughout the year in the highly leached acid soils of this zone have been reported, nor has nitrification of the soil nitrogen during incubation been systematically studied, but several determinations of the density of nitrifying bacteria have been made (Dommergues, 1952*a*; Berlier, Dabin and Leneuf, 1956; Jacquemin and Berlier, 1956). The studies by Dommergues cover a range of acid forest soils. In all these the numbers of nitrifiers under forest were found to be exceptionally low. In contrast to the low nitrification in these soils, ammonification proceeds readily (Dommergues, 1952a). On clearing, burning and subsequent cultivation large increases in the numbers of nitrifiers occur (Dommergues, 1952a; Jacquemin and Berlier, 1956), associated with the increase in soil pH (p. 67).

The data from Aiyinasi, Ghana (Table 10, example 1) indicate that even after 8 years of cultivation the pH did not fall below 5 in the top 6 in. of soil (under adjacent forest it is c.4·5). It therefore appears very unlikely that any significant decline occurs in the rate of mineralization in the brief two-year cropping period of native practice. This would accord with the lack of response of maize to nitrogen fertilizers found at this site.

### Moist semi-deciduous forest

Under forest of this type, the associated neutral to slightly acid soils contain well humified organic matter of C/N ratio 9–11 (Table 7). As might be expected nitrification is much more active than under moist, evergreen forest. This has been shown by studies of the soil-nitrate level and nitrifiable nitrogen throughout the year (Greenland, 1958) and the density of the nitrifying bacteria (Laudelout and du Bois, 1951; Dommergues, 1956). After clearing and burning, nitrification continues to proceed actively in the soil (Diamond, 1937; Hardy, 1946; Greenland, 1958) and even after several years of cropping there is no evidence of a significant decline in the soil-nitrate levels, although at Ibadan, Nigeria, Vine (1953*b*) found that nitrate levels fell significantly after 8 to 10 years and that nitrogen responses were then obtained. Direct comparison of these soils under forest and under cultivation shows that nitrification is slightly more active in the forest soil. Both nitrate and mineralizable

nitrogen levels are higher (Greenland, 1958) and also the density of the nitrifying organisms (Dommergues, 1956). The reason for the greater nitrification under forest is probably the high rate of addition of fresh and readily decomposed organic material from the vegetation.

### The savanna areas

The dominant factor affecting nitrate levels in savanna areas is the nature of the vegetation. Irrespective of the C/N ratio of the soil, its pH or moisture regime very little, if any, nitrate nitrogen is found in the soil while the dominant vegetative cover is a grass. This has been reported from India (Leather, 1911); South Africa (Theron, 1949 & 1951); Ceylon (Eden, 1951); Uganda (Mills, 1953); Southern Rhodesia (Saunder, 1954); the Ivory Coast (Berlier et al., 1956) and Ghana (Greenland, 1958). It is also well known in temperate regions. The degree of repression of nitrate level depends on the length of time for which the land has been under grass. Theron and Haylett (1953) suggested that 3 or 4 years are necessary for true grassland conditions to develop in the South African veldt, and Mills (1953) reports levels under a 3-year-old elephant-grass fallow in Uganda rather higher than is usual for permanent grassland. Greenland (1958) also observed levels higher than in permanent grassland under a 2-year old *Panicum maximum* fallow at Pokoase in Ghana.

The effect of the age of the fallow may be allied with the species of grass, since it has been observed near Johannesburg in South Africa that species occurring late in the natural succession are very sensitive to mineral salts (Roux, 1954; Jong and Roux, 1955). Ammonium sulphate, sodium nitrate and sodium sulphate tend to repress the growth of such grasses rather than stimulate it, apparently because the grasses are very sensitive to even very low salt concentrations. Use of ammonium-sulphate fertilizer on the natural grassland causes a reversion from late species to those normally occurring earlier in the succession. It seems that the grasses appearing late in the succession cannot thrive until low soil-solution concentrations have been induced. It is possible that these grasses are also the most active in preventing high soil-solution concentrations by checking nitrification.

This repressive action of grasses on nitrate levels is undoubtedly responsible for the very pronounced nitrogen deficiencies which occur when old savanna fallows are cleared. The persistence of the effect on clearing no doubt depends on the age and composition of the grassland. Meyer (1959) in the Congo basin found rapid ammonification and nitrification after clearing grasses (unspecified) which had been planted eight years previously on a forest soil. Mills (1953) in Uganda observed differences in nitrification in cultivated plots after 3-year fallows of *Pennisetum purpureum*, *Chloris* sp. and *Paspalum* sp. Mineralization was rapid after the

*Pennisetum* and very slow after *Paspalum*. Griffith (1951), also in Uganda, found that nitrate levels on land newly opened from *Pennisetum purpureum* or *Imperata cylindrica* remained at a relatively low level compared with long-cultivated plots throughout the first year of cultivation, but that normal levels for cultivated land were attained in the second year. He also reports that similar observations have been made in Queensland. Corresponding data for nitrate levels in land immediately after clearing fallows dominated by Andropogoneae are not available, but it is probable that similar effects would be observed. It might however be more difficult to detect in soils of much lower total nitrogen than those under elephant grass in Uganda.

There is no evidence of an important decline in the rate of mineralization with continued cultivation. Greenwood (1951), (Greenland (1958) and Hagenzieker (1957) have all observed active mineralization in savanna soils after several years of cultivation.

One reason for this may be the importance of soil drying in determining the amount of nitrogen mineralized in a cultivated soil. While it has been known for many years that drying will increase the amount of nitrogen mineralized (cf. Lebedjantzev, 1924), it is only relatively recently that attention has been directed to its importance in determining the typical nitrate-fluctuation pattern in tropical soils (Greenland, 1958) and any systematic investigation of its significance made (Birch, 1958). The reasons for the effect are still obscure, but it is probable that it is partly due to a change in the chemical form or combination or state of colloidal aggregation of the organic nitrogen compounds and partly due to modifications in the soil microflora. If nitrogen availability is determined largely by a seasonal influence such as soil drying then naturally over a limited number of seasons there will be no obvious systematic decrease in the nitrogen-mineralization rate.

The evidence available from soil-nitrate studies therefore indicates that in the oxysols of the evergreen-forest zone nitrification improves on clearing and burning but may thereafter decline slowly with cultivation, though it may be very many years before it falls to the level prevailing under forest. In the ochrosols of the moist semi-deciduous forest there may be some slight worsening relative to the soil under forest, nevertheless the humus continues to be mineralized at a rate more than sufficient for crop demands. In the savanna zone there is a steady improvement during the first one or two years after clearing from grass, and thereafter the limited evidence available suggests that the mineralization rate changes little for several years.

One further point that has been clearly demonstrated by soil-nitrate studies is the importance of early planting to make best use of the soil nitrogen. Nitrification proceeds rapidly in almost all cultivated tropical soils during the first rains after a dry season, or

even dry period. Nitrate levels increase rapidly, but these high levels generally last for only a few weeks. Continual rainfall not only causes losses of nitrate through leaching, but is accompanied by the proliferation of the heterotrophic soil population which competes with the crop plants for the nitrate supplies, and by the development of wetter, less well aerated soil conditions which promote increased activity of the denitrifying organisms in the soil. To take advantage of the high levels of soil nitrate planting should take place immediately following the start of the rains. The great superiority of early planting, has been confirmed for cereal crops by a series of experiments in Nigeria (Kowal, priv. comm.) and by East African experience (Hagenzieker, 1957; Russell, 1958). This has however long been recognized in local practice, and early planting is widely recognized as the hallmark of the good peasant farmer. It does, however, call for nice judgement since in many parts an early storm may be followed by a drought long enough to shrivel young seedlings.

Profit from a release of nitrogen is not the only advantage to be gained from early planting, since Cutting *et al.*, (1959) find the practice benefits cotton and legumes, which do not usually respond to nitrogenous fertilizers. A parallel mineralization of organic phosphorus, a quick cover ahead of the weeds, an early established root system and the timing of planting in relation to pest attack are only some of the factors that may be involved in a particular case.

(iv) *Changes in total soil nitrogen*

The annual loss of soil nitrogen during a cropping period is given by

$$-\frac{dN}{dt} = kN - k_1 \text{ (Dawson, 1950)}$$

where k is a rate factor, N the total soil nitrogen and $k_1$ is the annual addition of fixed nitrogen to the soil. In most instances $k_1$ may be expected to be small in relation to kN, so that, as with humus decomposition, a simple exponential law is followed. Also as the C/N ratio changes little during cultivation (Table 7) k will be closely similar to $k_c$, the soil humus-decomposition constant. For a forest soil containing 0·10% nitrogen, in which 4% of the total is mineralized per annum, the annual release of mineral nitrogen from the top 12 in. (4 million lb.) of soil will be 160 lb., or sufficient for two good crops. If any nitrogen removed in the crops is derived from atmospheric nitrogen by symbiotic or non-symbiotic fixation, more than sufficient will be released. For a savanna soil of 0·03% total nitrogen the corresponding figure for nitrogen mineralization is 48 lb. The relative rarity of nitrogen responses in the forest zone, except when total levels have seriously declined, and their frequency in the savanna zone, even after the effect of the repression of nitrate levels by grasses has disappeared, is therefore readily understood.

(v) *Changes in the phosphorus status*

It is only recently that techniques have been developed for measuring the exchangeable pool of phosphorus which may be readily utilized by plants. Changes in total soil phosphorus during a period of cropping are relatively so small that they cannot normally be measured. Consequently it is not surprising that most workers have not attempted to determine the effects of cultivation on soil phosphorus. The conventional methods for estimating the phosphate status of the soil, using various extractants, have been examined in East Africa by Birch (1952 and 1953), in Central Africa by Saunder (1956) and Pawson (1957), and in West Africa by Nye and Bertheux (1957). These authors have not found any generally valid method of estimating the availability of soil phosphorus, although arbitrary and empirical relationships may be established between the soil phosphorus determined by a particular technique and responses to phosphate fertilizers in the field for a limited range of soils. While such relationships may be useful for advisory purposes they do little to advance our knowledge of the state of the phosphate in the soil, and its relation to crop growth. It is thus apparent that in the three examples of Tables 10 and 11 where phosphate measurements are given, they are of little quantitative value. Nevertheless all three show a pronounced fall with cultivation in the amounts of extracted phosphate.

It seems likely that one of the main functions of the fallow on phosphate-deficient soils is to raise the phosphate availability, chiefly through the ash added when the fallow is cleared. The large rise in the readily extracted phosphate that follows burning has already been noted. This rise corresponds to the initial adsorption of the added phosphate into the exchangeable pool. The availability will vary from place to place in the soil, depending on the local concentration of phosphate in the pool. With cropping the availability will decline because (a) there is a general tendency to equalize the availability of the phosphate throughout the whole mass by diffusion, (b) plants not only take up phosphate, but they feed preferentially on spots of high availability, so reducing their phosphate level faster than spots of lower availability, (c) the gradual aging of the insoluble complexes in which the phosphate is bound is accompanied by more perfect crystallization and hence a reduction in availability.

This reduction in the availability of added phosphates is often referred to as fixation. It is widely held that tropical soils "fix" added soluble phosphate rapidly into unavailable forms. This view has been derived from observations on soils with a high content of free iron and aluminium oxides derived from basic rocks. However, within the wide scope of tropical soils these must definitely be considered a minority (see p. 20). The more widespread soils developed from quartzose rocks with a higher silica/sesquioxide

ratio in their clay fraction do not appear to fix phosphate so rapidly. This is evidenced by the high residual effects of phosphate fertilizers that have been shown in West and East Africa to persist at least into the third year (Nye, 1954; Stephens, 1960*c*; Greenwood, 1951; Birch and Friend, 1957). Thus the effects of the phosphate provided by the ash of a fallow, equivalent to some 300 lb./acre of single superphosphate (24 lb. P) from a 10-year forest fallow and 50–100 lb. (4–8 lb. P) from a grass fallow, should persist for the normal cropping period, though with diminishing effect in successive seasons.

Some phosphorus will also be released by mineralization of humus during the cropping period. For a forest soil containing 50 p.p.m. organic phosphorus, of which 4% is decomposed per annum, the release in the 0–12 in. layer in one year is 8 lb. per acre of phosphorus. In a savanna soil with only 20 p.p.m. organic phosphorus the corresponding figure is 3 lb. per acre.

(vi) *Changes in the amounts and availability of nutrient cations*

The amounts of exchangeable cations in the soil are the measure of the size of the pool which plants may draw on immediately. The availability of a cation in this pool will depend on the type of exchanger (usually humus and kaolin in examples considered here), the proportion of the total exchange capacity which it satisfies, and the other cations present.

During cropping the quantities of exchangeable cations will tend to be reduced by leaching and plant removals. Release from non-exchangeable forms may compensate these losses, at least to some extent. The loss of cations tends to reduce their percentage saturation in the exchange complex, and correspondingly their availability, but this may be compensated by an overall reduction in exchange capacity due to humus oxidation. We are therefore concerned with changes in the exchange capacity as well as the individual exchangeable cations.

The limited evidence regarding changes in exchange capacity given in Tables 10 and 11 is not conclusive. In no instance is there the decrease in exchange capacity that would be expected if it were primarily accounted for by the soil humus, for the losses in humus and exchange capacity are not in constant proportion. In some instances increases are noted, particularly in the 6–12 in. soil layer. The apparent slow declines or even increases in exchange capacity may not be genuine effects since exchange capacity may well be rendered low by aging in storage. This would be more likely to affect samples taken at the outset of an experiment than those taken at its conclusion.

With regard to the individual cations the amount of exchangeable calcium decreases in all instances, except in the oil-palm intercropping experiment at Benin. With potassium an increase was observed at Aiyinasi over 8 years and in Guatemala after one, and a decrease in the intercropping experiment, and at Sefa, Senegal.

Aging of samples in storage may account for the apparent increases observed.

Obviously with so little evidence it is not possible to draw very firm conclusions, but it is probably safe to say that no large decreases in the exchangeable cations in the soil are likely to occur after a single cropping period of one to three years. Deficiencies may well arise with continued cropping, or with intermittent cropping and fallow periods insufficient to make good the losses, but simple measurement of the quantity of exchangeable cations is unlikely to reveal this.

Further evidence about changes in the availability of nutrients is provided by studying changes in soil pH. This is a rough measure of the percentage saturation of the exchange complex by nutrient cations, for as the percentage saturation of the exchange complex increases from 0 to 100, the pH (in water) increases from about 4·0 to 7·0 (the exchange capacity being arbitrarily defined at pH 7·0). For a wide range of forest soils in Ghana, whose colloid is in the main humus and kaolin, Endredy and Montgomery (1956) find there is a linear relation between pH and percentage saturation. As will be seen in Tables 10 and 11 changes of the pH are in general very slow, even over cropping periods of several years, which implies that not only is the fall in quantity of exchangeable nutrients small, but also that their availability remains steady.

Measurements of pH do not of course tell us in detail about the availability of individual cations such as potassium and magnesium, and to assess their availability it is usually necessary to know at least the proportion of these cations in the exchange complex. Thus, for instance, Tinker and Bull (1957) have found that oil palms, growing on poor sandy soils developed from tertiary sediments in south-eastern Nigeria, show symptoms of potassium deficiency when less than 1·5% of the exchange capacity (in equivalents) is satisfied by potassium. The percentage potassium saturation proved a better index to the health of the palms than the total amount of exchangeable potassium.

In a rotation trial on a forest ochrosol in Ghana, Stephens (1960*b*) found yields of maize and cassava to be severely reduced by potassium deficiency after 7 years of continuous cropping. The potassium saturation percentage had fallen to 1·2%. When an elephant-grass fallow was included in the rotation the yields were maintained and the potassium saturation percentage was 2·4%.

In the continuous factorial trials in Ghana, some of whose results are shown in Table 9, the potassium saturation percentage in the plots showing small responses to potassium by maize and large responses by cassava ranged from 0·9 to 3·7%. In the trials showing no response by cereals or yams the corresponding values ranged from 3·1 to 10·2% (Stephens, manuscript).

Saunder (1954) reports for Southern Rhodesian soils, that preliminary indications show the potassium saturation percentage should exceed 1·0% for maize.

Many of the soils of the forest have values of potassium saturation near or below 1·5%. As would be expected there is some tendency for the potassium saturation percentage to be lower in the acid oxysols than in the less acid ochrosols. The calcium and magnesium saturation percentages undergo a much greater change. Thus large numbers of samples from the 0–9 in. layer under different classes of vegetation in the forest region of Ghana had the following average values (calculated from Charter, 1955).

| | No. of samples | pH | Exchange capacity | Exchangeable cations | | | % Saturation | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Ca | Mg | K | Ca | Mg | K |
| | | | | mc./100 g. | | | | | |
| Ochrosols | 127 | 6·5 | 12·04 | 8·48 | 1·90 | 0·36 | 70 | 16 | 3·0 |
| Oxysol-ochrosols | 36 | 5·3 | 9·49 | 4·02 | 1·00 | 0·26 | 42 | 11 | 2·7 |

The difference in the potassium saturation percentage was small. It seems therefore that soils over the whole forest region, and not merely the acid soils, are liable to be deficient in potassium.

Although the exchangeable-K levels in much-cropped savanna soils are frequently as low as 0·1 m.e. per 100 g. the exchange capacity is also low and in Ghana (de Endredy—priv. comm.) and Northern Rhodesia (Ballantyne, 1958) the saturation percentage is rarely below 1·5% on the kaolinitic soils for which this limit holds good.

3. *Reasons for the decline in nutrient levels*

Though there is no doubt about the decline in the level of nutrients during the cropping period, there is no clear realization of the way in which they are lost, nor any appreciation of the capacity of the soil to sustain these losses over repeated periods of cropping. Conclusions about these questions must necessarily be tentative because of lack of data, but a discussion of them here should focus attention on the need for further work.

Nutrient levels in the soil will fall during cropping because of their removal in crops, and loss by erosion and leaching. If we are to understand this vital aspect of the decline in fertility we must attempt a quantitative assessment of the relative importance of these factors.

(i) *Crop removal*

We may use the data given in Table 4 to estimate the amounts of nutrients removed during a cropping period in forest and savanna. For example in forest a reasonable production per acre over a period of three years of 1000 lb. maize, 500 lb. groundnuts (kernels), 10,000 lb. plantain, and 10,000 lb. cassava may remove 106 lb. N, 12 lb. P, 120 lb. K and 7 lb. Ca. By comparison a 17–18-year fallow on one acre releases on clearing 40 lb. P, 233 lb. K and 170 lb. Ca (see Table 8). Further amounts of about 480 lb. N (see p. 111) and

24 lb. P (see p. 113) may be released during 3 years of cropping by mineralization of the humus, and an unknown amount of atmospheric nitrogen will be fixed.

We may conclude that crop removal makes a significant contribution to the loss of potassium and to a lesser extent of phosphorus. The removal of potassium will be increased by greater production of carbohydrate crops like cassava, yam, cocoyam, sweet potato and plantain which have a high potassium content.

In the high-grass savanna a production over 3 years of 5,000 lb. yams, 1,000 lb. maize or other cereals, 500 lb. groundnuts (kernels), and 5,000 lb. cassava per acre may remove 68 lb. N, 8 lb. P, 54 lb. K and 4 lb. Ca. Total clearing of well wooded savanna may release about 20 lb. P, 170 lb. K and 240 lb. Ca, but in land that is more intensively used, the clearing of the grasses alone may provide only 7 lb. P, 41 lb. K, 31 lb. Ca. Mineralization of humus may release a further 150 lb. N (see p. 111) and 8 lb. P (see p. 113). Thus, except when the fallow is well wooded crop removal could account for most or all of the P and K added on clearing the fallow, and by mineralization of the humus.

(ii) *Erosion*

In a forest soil under crop the greatest concentration of nutrients is in the top 3 in., provided the surface is not much disturbed by cultivation. Under normal native practice, on slopes less than 10 per cent, loss by erosion during three years of cropping should not exceed 50 tons per acre and will usually not come near this amount. Thus, the loss is at most about one tenth of the fertile 3-in. layer. In spite of the fact that the eroded soil may be richer than the remainder, such a loss during a single cropping period will have little effect on the availability of nutrients in the top soil. It seems therefore that erosion can scarcely be held responsible for a rapid decline in fertility except where catastrophic erosion occurs. In savanna, where cultivation methods do not maintain nearly such an effective cover over the ground, where there are no effective controls, where the soil is much more erodible, and ridges may run up and down the slopes as an aid to drainage, losses may well be greater. Nevertheless the loss of as much as 100 tons over a three-year period—one tenth of the 0–6 in. layer, will not cause a serious reduction in yields in one cropping period. Such losses are of course very serious in the long run, especially on shallow soils as has been explained on p. 89.

The effects of erosion on the soil nutrient reserves after repeated cycles of crop and fallow are further examined in section 4 of this chapter.

(iii) *Leaching*

On clearing and burning, the cations furnished by the ash, mainly as calcium, magnesium, sodium and potassium carbonates

and silicates, will react rapidly with the soil and be absorbed in the exchange complex. In view of the oft-repeated statement that on burning the fallow releases soluble salts that are rapidly leached it is worth noting that the fallow does not release any significant quantity of anions that will hold cations in the soil solution (see p. 41). Silica does not ionize to any extent below pH 9, phosphate is almost completely absorbed, and chloride balances but a very small fraction of the cations. In the neutral to acid soils with which we are concerned it is primarily the nitrate ion that holds cations in the soil solution in the top soil. The bicarbonate ion is of little significance compared with nitrate below pH 6. In some circumstances the immediate top soil may be raised to a pH above 7 by the alkaline ash, and cations, held in solution by bicarbonate ions, may be rapidly leached into the lower top soil, but they are unlikely to be lost below the top 12 in. where the pH is lower.

The rate of leaching will depend on the product of the rate of percolation and the concentration of ions in the soil solution. It is therefore clear that while the level of nitrate in the soil must be adequate for crop growth, in forest high levels are bad, not primarily because they lead to loss of nitrogen which is in fairly liberal supply, but because they lead to loss of cations, particularly potassium.

Some idea of the quantitative importance of this loss may be derived. We have seen that on clearing secondary forest about 480 lb. of nitrogen are released in 3 years. If all this was leached it would carry with it 34 lb.-equivalent of cations. This compares with 20 lb.-equivalent provided by the ash of an 18-year forest fallow. About 100 lb. of nitrogen will be taken up by crops, and denitrification will account for a further unknown amount. These uncertainties emphasise the need for lysimeter studies to determine leaching losses accurately. In savanna, leaching will be less rapid because much less nitrate is released.

The assumed rapid loss of nutrient cations in the moist evergreen forest is usually attributed to the intense rainfall of this region. According to the argument we have presented variation in the rainfall has little influence on these losses provided it is sufficient to cause through leaching of the top soil. The important factor is the nitrate provided for leaching and the cations that must accompany it.

Losses of phosphate by leaching are negligible (see p. 42). The decline in the phosphate status of the soil with cropping is due partly to the uptake by crops, and to the fall in its availability, as already discussed.

### 4. *Nutrient losses in relation to soil reserves*

When fertility declines because fallows are much too short it is primarily because of exhaustion of nitrogen, phosphorus and potassium in the top soil. We have, however, to consider whether fertility will inevitably decline, even granted long fallows, because of

a more deep-seated exhaustion not only of the top soil, but also of the subsoil from which it normally recuperates.

It is widely held that the fertility of the soil cannot be maintained indefinitely by shifting cultivation. For example, F.A.O. (1958) state that "at each turn of the cycle the soil becomes more depleted of nutrients and its productivity is less, and more short-lived." Clearly if the soil is severely eroded during the cropping phase, or forest land is transformed into a savanna the fertility is not maintained. But provided these excesses are avoided and fallows of reasonable length are allowed, does the soil undergo a decline in fertility, and if so at what rate? The question is of considerable interest to the past as well as the future, for if the depletion of reserves with each cycle is considerable then it would set a limit to the time that the forest regions can have supported their population.

(i) *The reserves of nitrogen*

It has been shown in chapter 5 that over a long period the level of humus and nitrogen in the soil will build up to a limit governed by the type and productivity of the vegetation. Thus, if the vegetation can be restored after cropping so also can the level of nitrogen. When a mature secondary forest is cleared there is no evidence that even considerable soil exhaustion caused by cropping will prevent the eventual development of a new secondary forest as productive of litter as the old. Thus it is well known that poor soils will support a luxuriant tropical forest, e.g. Richards (1952), and the high litter falls obtained on very poor soils in the Belgian Congo, shown in Table 5, are further evidence of this point.

Although after cropping the level of nitrogen can be restored to any extent short of the 'virgin' level by a sufficiently long fallow, the rate of restoration may decline in successive cycles. Thus Cook (1921) has noted that in Central America the rate of forest regrowth becomes slower after each cropping period. It is likely that this is due to increasing shortage of other essential nutrients.

(ii) *The reserves of phosphorus and potassium*

Though the level of nitrogen may be maintained by long fallows, losses of other nutrients by erosion, leaching and crop removal must be made good from the subsoil; and this will itself be depleted by successive cycles of fallowing and cropping. The losses of phosphorus and potassium are likely to be specially significant, and we must therefore attempt to relate them to the total reserve of these elements in the soil.

The stock of usable nutrients is contained not only in the exchangeable pool but also in the non-exchangeable reserve, since over long periods substantial amounts will be released from non-exchangeable to exchangeable forms. In a mature soil profile, containing few unweathered primary minerals, there is probably a fairly constant proportion between the exchangeable and a part

of the non-exchangeable forms of phosphorus and potassium. The exchangeable pool may undergo rapid depletion during the cropping period, but the loss is partially made good by slow release from the non-exchangeable forms till the characteristic proportion is attained. Unfortunately we have little idea of the extent to which the non-exchangeable reserve enters into this long-term equilibrium.

There is also great uncertainty about the contribution of the subsoil to the reserve of phosphorus and potassium. As shown in chapter 4, the nutrient cycle is very rapid under forest or vigorous grasses. Over a long period the fallow will tend to distribute the usable nutrients in the top soil and the subsoil within its root zone in a characteristic ratio. Thus the amounts of total phosphorus in the top soil under forest are usually higher than amounts at lower depths, but the amounts of total potassium show no systematic change down the profile. As nutrients are removed from the top soil by cropping, long fallows should serve to maintain the characteristic balance between top soil and subsoil. On this long-term view, therefore, the total reserve of nutrients will extend to the whole effective rooting depth of the fallow. Over shorter periods the capacity of the fallow to make good from the subsoil the losses from the top soil will be reduced.

Before any reliable estimate can be made of nutrient reserves in relation to losses by cropping far more work needs to be done on the amounts of nutrients in non-exchangeable forms, their equilibrium with exchangeable forms, and the extent to which they are taken up from the subsoil. Essential knowledge is also lacking on the extent of leaching losses particularly during the cropping period.

Some indication of the total amounts of nutrients in tropical soils has been given on p. 26. As a specific example, a soil with near-average values of total phosphorus and potassium among forest soils in Ghana, (200 p.p.m. P and 600 p.p.m. K) contains about 4,000 lb. total phosphorus and 12,000 lb. total potassium in the top five feet. During a three-year cropping period about 12 lb. phosphorus and 120 lb. potassium might be exported in crops and a further unknown amount of potassium leached (see p. 117). It would seem therefore that, providing most of the non-exchangeable nutrients enter into a long-term equilibrium, reserves are in general substantial, and with reasonably long fallows cropping should be possible for many cycles. On exceptionally poor soils potassium is the element whose reserves are most likely to be exhausted by several periods of cropping.

As regards losses by erosion, the removal of, say, 20 tons of top soil in each cropping period represents a loss of 8 lb. per acre P and 32 lb. per acre K on the soil just mentioned, without allowing any enrichment in the eroded soil. At the same time the whole surface of the soil is being lowered so that these losses are compensated by the fresh layers of subsoil that come within the range

of the roots of the fallow. Of course if the rooting depth of the fallow is restricted, notably by iron pan in savanna regions, losses of nutrients by erosion are serious. In such instances, the soil is eventually restored by erosion of the pan itself, but this is a process that must be reckoned in periods of geological time and scarcely concerns us.

Throughout this discussion it has been assumed that nutrients removed in crops are not replaced. This is true of populations settled in permanent homesteads if no attempt is made to return refuse to the land. Nomadic cultivators on the other hand leave their temporary settlements enriched by their refuse, and there is thus a nearly total, though erratic, return of all nutrients to the land. Richards (1939), for example, describes how the Bemba, who inhabit the 'miombo' of Northern Rhodesia and move their huts every 5 years or so, deliberately seek out these old settlements for their gardens; and it is widely known that irregular patches of soil with a high level of soluble phosphorus are an indication of old settlement sites. If these sites are effectively utilized, it should be possible to continue cropping with adequate fallows almost indefinitely, particularly in savanna regions where leaching losses will be low.

(f) Changes in the Soil Fauna and Flora

It is not known how far changes in the soil population are caused by falling soil fertility, and how far, if at all, such changes contribute to its decrease. They may have some effect, and it is therefore appropriate that they should be considered. Few critical studies have been made in this field, and their value is limited by imperfections in the techniques available, and lack of knowledge of the factors which control the ecology. Even for such important components of the soil fauna as worms and termites there is no quantitative data to indicate the effects of cultivation on their abundance, and for termites no general agreement about their effect on the soil. No attempt can be made here to give a critical account of techniques available for measuring soil-population changes, but reference may be made to the recent symposium on soil zoology (Kevan, 1955) and a recent review of soil microbiology (Thornton and Meiklejohn, 1957). The importance of season in determining changes in the soil fauna has been shown by Strickland (1947) in Trinidad and Belfield (1956) in Ghana, and in determining changes in the soil microflora by Castagnol and Cong-Vien (1951) in Vietnam, Boquel *et al.*, (1953) in the Ivory Coast, Dommergues (1954*d*) in Madagascar, and Meiklejohn (1957) in Kenya. These studies show that season is important in determining both the total population of the soil and its composition. Samplings made at only one or two dates are therefore of limited value in determining the effects of cultivation. Because of this the studies that have been made will be only briefly considered.

1. *Changes in the Soil Fauna*

On the basis of samples taken on a limited number of dates Maldague (1959) has reported an overall decline in the soil population on cultivation of forest soils in the Belgian Congo. In more detailed studies Strickland (1947) in Trinidad and Belfield (1956) in Ghana have reported a seasonal migration from the top soil in cultivated land, that is associated with the more intense drying of this layer compared with what occurs when the soil is under its natural vegetation. Salt (1955) reports a decrease in numbers on cultivation of soils previously under elephant grass in Uganda, but again on the basis of a few sampling dates only. The numbers of soil animals under elephant grass appear to be greater than under most savanna grasses, where they are generally low (Strickland, 1947; Salt, 1952 and 1955; Belfield, 1956: Maldague, 1959). It seems likely that in the drier savanna areas the effects of cultivation are relatively slight.

2. *Changes in the Microflora*

The changes which take place in the microflora on clearing and burning have already been discussed. There is an immediate and very large increase in numbers in the oxysols, but relatively little change in the forest and savanna ochrosols. Subsequently the numbers decline relatively rapidly in the oxysols (Corbet, 1934; Dommergues, 1954*a* & *b*) and slowly in intermediate soil types (Dommergues, 1952*b*). It is possible that a slow decline also occurs in the ochrosols proper as Dommergues (1956) found a lower activity in such a soil under cultivation than in the same soil under forest, but this result was based on only two sampling dates. In general the ochrosols appear to be characterized by a great stability in both the numbers and composition of the soil flora (Laudelout and du Bois, 1951; Dommergues, 1954*a* & *b*). If erosion intervenes a rapid decline in the soil population may be expected whatever the soil type (Dommergues, 1952*b*, Bosser *et al.*, 1956).

The range in magnitude and composition of the population of the ochrosols is similar to that of temperate brown earths. In the more highly acid oxysols a predominantly fungal population may develop (Corbet, 1934) though not invariably, since Laudelout and du Bois (1951) and Laudelout and d'Hoore (1949) never found this in a wide variety of highly acid soils in the Belgian Congo. The relationship between the microflora of ochrosols and oxysols appears to be similar to that between the flora of temperate mull- and mor-type soils. The low total numbers of micro-organisms in the oxysols indicates that a more resistant type of humus less able to support a highly active population is developed. The negligible decline in numbers of micro-organisms in the ochrosols during cultivation, and the fact that in the oxysols the immediate increase is followed by a decline to not less than the level which obtained

under forest indicates that cultivation causes no decline in the ability of the humus to support the activity of soil micro-organisms.

## The Cropping Period—Conclusions

In this Part we set out to examine the changes that take place in the soil during the cropping period, and to enquire why yields decline, and why farmers leave the land to clear a new plot. Under separate headings we have traced the effect of clearing and cropping on the physical, chemical and biological properties of the soil; and have examined the effect of these soil factors and the incidence of pests, diseases, weeds and erosion in causing declining yields.

All these separate elements may now be integrated in a comparison of the main processes taking place in the different ecological zones at both low and high intensities of cropping.

### *Forest*

The labour of clearing virgin forest is considerable. Hence mature secondary forest is often preferred, although virgin forest may be cleared in order to obtain rights over the land, timber for building and logs for canoes.

In either case, following clearing and burning the land is free of standing weeds, its physical condition is excellent and no cultivation is required before planting. In the equatorial regions, particularly in the Congo and West Africa, the soil is well protected from erosion by the practice of following the first planted cereal by a succession of semi-perennial crops. This also reduces the labour of weeding to a minimum.

In other parts of the tropical forest region it is usual to plant two annual crops in succession (e.g. rice in the second year in Asia, or maize or groundnuts in the second season of the first year in Africa). The second clearing and burning that this usually necessitates weakens suckers, destroys seedlings, and encourages grasses. Invasion of weeds is more serious in south-east Asia than in other parts, because of the aggressiveness of *Imperata cylindrica* there. The exposure of the soil may lead to erosion, particularly on the steep slopes characteristic of forest regions. Another practice which accelerates the deterioration of the soil is the use of the hoe to build mounds for such crops as yams and sweet potato.

On clearing and burning the forest the large addition of nutrients in the ash raises the availability of the important nutrient cations to a satisfactory level for the first crop. A liberal supply of nitrate is furnished by mineralization of the humus. Even in the acid oxysols nitrification is rapid following the increase of pH promoted by the burn. The high nitrate levels may however lead to a rapid loss of cations, which are leached in proportion to their equilibrium concentrations in the soil solution. In some forest soils, e.g. in the Central Congo, Ghana, and Southern Nigeria it seems that the

availability of potassium may soon limit crop growth. The critical level is related to the percentage saturation of the exchange complex by potassium. This is to some extent correlated with increased rainfall and low pH, but latosols deficient in potassium are liable to occur throughout the forest region. The decline in the level of potassium is accentuated by carbohydrate crops such as cassava and plantain, which take up large amounts of this element, and it seems likely that its deficiency may be the main reason for declining yields. Phosphate may be deficient for maize or rice, even though they are the first planted crops, but cassava, following later, appears to be less sensitive.

If plots are maintained under a succession of annual crops there is evidence that yields even in virgin or mature secondary forest land fall fairly rapidly. The native farmer, however, does not attempt to crop his land for long enough for declining fertility to be a dominant factor, because of the labour of weeding. It costs him less effort to clear another patch of ground.

As land becomes scarcer the farmer has to clear land rested for shorter periods. He does not seem as a general rule to respond to increasing pressure on the land by cropping longer.

When fallows become short there is a tendency for savanna to become established, particularly on the margins of the forest. In south-east Asia a fallow of some 10 years is the minimum for control of *Imperata* before the next cropping period. However, in other parts shorter-term woody fallows are being successfully maintained: for instance at Umuahia in south-east Nigeria, where it has been found that if grasses are checked by careful weeding, the minimum of burning is done and the stumps of the fallow are carefully preserved so that it will coppice freely, it is possible to follow $1\frac{1}{2}$ years of cropping with only $2\frac{1}{2}$ years of a fallow of *Acioa barteri* even on a soil inherently low in mineral reserves under a rainfall as high as 90 in. (Vine, 1954).

As the period of fallow declines so does the amount of phosphorus and potassium added in the ash, the level of humus, and the amount of nitrogen and phosphorus mineralized from it. Consequently the availability of nitrogen and phosphorus will be reduced. Consistent responses to nitrogen have been obtained on forest soils when the period of fallow becomes short. The availability of potassium will not necessarily be reduced because, owing to reduced exchange capacity, its proportion in the exchange complex may be maintained. The system is however less well buffered in potassium, and leaching and crop removal will lead to a more rapid decline in its availability during the cropping period. Such intensive cropping as that practised in the example quoted from south-east Nigeria gives a low return for the effort expended, but the whole region is so overcrowded that the people cannot move. Cropping at this intensity probably represents the maximum return which can be obtained from a given area of land over a long period by

methods of 'bush' fallowing alone. Further reduction of the fallow period would so reduce fertility that the decrease in yields would offset the extra time available for cropping.

More intensive cropping is possible only if nutrients are supplied to the soil. It is very common for settlements to be surrounded by continuously cropped and carefully tended 'gardens', 'beds' or 'groves' whose fertility is maintained by the refuse of the household, but the area that it is possible to treat in this way is small.

*Savanna*

While traditional practices in the equatorial-forest region and to a lesser degree in the monsoon region are admirably adapted to conserving the physical and chemical condition of the soil, those of the savanna region have no such obvious merits.

The physical constitution of the soil developed under the savanna grasses is much poorer than under a forest fallow. This is due largely to dry-season burning which reduces the litter and exposes the surface to the destruction of the early rains. A good constitution in the surface inch would in any case be of limited benefit, for a thorough hoeing is essential to clear the grasses for cultivation. The loose soil heaped into mounds or ridges is exposed and easily eroded. However the farmer is more worried about drainage and the need to dispose of storm water without loss of his seedlings than about the loss of top soil, and so he often builds ridges that run up and down the slope; understandably, he works by pulling the soil downhill towards him. The soil is bared afresh at the beginning of each cropping season, because the dry season prevents the growing of crops which would form a protective cover. When the land is abandoned after about 3 years the fallow is slower to regenerate than is the forest fallow, owing to the scarcity of suckers and established seedlings.

To some extent these disadvantages are mitigated by the fact that the drier savanna lands are associated with gentle slopes. However, such areas are also those which frequently have iron-enriched horizons near the surface, and if these are not already indurated they may become so as the surface is stripped by sheet erosion. In areas of savanna recently derived from forest, slopes may be steep, and gulley as well as sheet erosion may be severe.

In the more humid savannas generally, the land is often abandoned after about three years because of weeds rather than a decline in its fertility. In the Ivory Coast and Ghana, for example, *Imperata cylindrica* may cause a move. In infested land farmers will try to avoid clearing until the *Imperata* has been shaded out by other high grasses, but pressure may be such that they are forced to clear younger fallows and to face rather more arduous weeding during the cropping phase. In the elephant-grass region of South Busoga, Uganda, the land is also rested after 3 or 4 years because of weeds.

In drier regions where cereals are the staple food crop, grass weeds are less difficult to control, but the parasitic weed *Striga* may force a rest.

Even when long fallows are possible cropping for more than 3 or 4 years is rare in savanna areas, and especially in drier regions it is declining fertility rather than weeds that lead to the land being abandoned. The main elements of this decline vary according to the length of the fallow.

In contrast to the mature forest, when old savanna is cleared, there is a shortage of available nitrogen in the first year of cropping. This appears to be most serious in the high-grass savanna dominated by the Andropogoneae. The shortage of available nitrogen has more serious effects on cereals than on some other crops, and native cropping practice often recognizes this. Thus yams are commonly planted as the opening crop on new land in the high-grass savanna of West Africa, and in other parts of Africa cotton or tobacco are preferred as the opening crop.

The organic-matter levels built up in the top soil under savanna are lower than under forest, and they appear to be insufficient to provide adequate levels of available nitrogen. Even on land cleared from old savanna, a shortage of nitrogen persists in the second and subsequent years of cropping. There is as a rule no shortage of phosphate in the first year or two of cropping long-fallowed land. In subsequent years increasing responses to phosphate fertilizers have been obtained.

When younger fallows of 2–6 years are cleared there is a shortage of nitrogen, but the deficiency is not so acute as that following the clearing of old savanna. In the old grasslands there appears to be some factor directly limiting nitrate formation that does not exist or exists to a lesser extent after the shorter fallows.

On these more intensively cropped soils phosphate may be deficient even in the first year after clearing, and where it is not deficient it will usually become so in a year or two.

In contrast to forest soils there is evidence from fertilizer trials and soil analyses that potassium rarely becomes deficient on savanna soils even when they are very intensively cropped. The reason would seem to be that while exchangeable potassium in savanna soils may be very low, so also is the exchange capacity, so that the proportion of potassium in the exchange complex is adequate. The maintenance of the level of potassium is due partly to the fact that nitrate levels are low so that there is little leaching of the cations. In addition, removal of potassium in crops is probably compensated to some degree by release of non-exchangeable potassium, which occurs in greater amounts than in the more thoroughly weathered forest soils. In the drier parts where grain rather than root crops are grown, comparatively little potassium is removed in the crops in any case.

The pH of savanna soils is very rarely below 5·0, and it changes little as the soil becomes more exhausted. Responses to lime have been obtained on a range of crops, but they are small.

There is evidence that sulphur and molybdenum levels are often marginal for groundnuts, but it seems likely that the shortage is confined to legumes, for it has not been observed on cereals. There is little indication that yields of subsistence crops are reduced by shortage of other elements under present native practices. If production is intensified by use of fertilizers, and higher-yielding varieties, deficiencies of the micronutrient elements might well be revealed.

# PART III—THE SYSTEM AS A WHOLE

## Chapter 7

## SOIL FERTILITY UNDER NATIVE PRACTICE

In this chapter we shall deal mainly with the long-term effects of native practices on the fertility of the soil. This as we have seen is partly an inherent quality depending on natural soil-forming factors such as parent material, climate and vegetation; but it is also a reflection of its cropping history.

The ratios of cropping and fallowing we have noted in reports from different regions are collected in Table 12. The list is by no means exhaustive, but serves to illustrate many of the points we wish to make in this chapter. Where the periods of crop and fallow are described as normal it is usually implied that cropping at that intensity could be prolonged for many cycles without noticeable erosion of the soil, a change in the type of fallow, or a marked decline in yields. On the other hand where the intensity of cropping is described as excessive it leads to erosion or rapidly declining yields, and these effects are usually associated with a deterioration in the quality of the fallow. Thus, intensive cropping with two years of crop and about 4 years of fallow on the southern margin of the moist semi-deciduous forest of Ghana under a rainfall of 45 in. p.a. distributed over two rainy seasons, is causing a regression in the fallow from secondary forest to densely coppicing thicket, which is in turn being replaced by grasses, *Panicum maximum*, *Andropogon* sp. and finally *Imperata cylindrica*.

In the superhumid forest regions of south-east Asia and Central Africa 1–2 years of cropping are normally followed by 10–20 years of fallow. In no normal example from the Far East does the fallow period fall below 8 years, and this, as we have seen, is due to the need to control *Imperata cylindrica*.

In the less humid forests and the savannas of Africa very much more intensive cropping, using the natural fallow alone to restore fertility, is possible. Cropping periods of some 2–4 years followed by 6–12 years of fallow are common and apparently stable in both the forest and savanna regions. The extreme under forest conditions which has already been mentioned is reported by Vine (1954): $1\frac{1}{2}$ years of cropping followed by only $2\frac{1}{2}$ years of woody fallow, maintained for at least 40 years on inherently poor soil. In the savanna there are many examples of 3 years of cropping being

## TABLE 12

### The Length of the Crop and Fallow Periods under Shifting Cultivation

| No. | Place | Rain in. p.a. | Crops | Fallow | Periods in Years: Normal C | Normal F | Excessive C | Excessive F | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| | | | | **Moist evergreen forest zone** | | | | | |
| 1. | Sarawak | c.150 | Hill rice | Forest | 1 | >12 | 2 | 12 | Early abandonment of land necessary to prevent invasion of *Imperata*. |
| 2. | Guatemala | 135 | Maize | Forest | 1 | >4 | | | 'Ando' type soil |
| 3. | Liberia | 80–180 | Rice, cassava | Forest | 1–2 | 8–15 | | | |
| 4. | Sierra Leone | 90–130 | Rice, cassava | Forest | 1½ | 8 | 1½ | 5 | Grasses (esp. *Chasmopodium* sp.) invade with excessive cultivation. |
| 5. | Assam | c.100 | Rice/millet, maize, rice | Forest | 2 | 10–12 | 2 | <7 | |
| 6. | Sumatra | c.90 | Rice, root crops | Forest | 2 | 10–16 | | | *Imperata* invades, but may give place to forest. |
| 7. | Phillipines | >100 | Rice, root crops, maize | Forest | 2–4 | 8–10 | | | |
| 8. | Nigeria | | | | | | | | |
| | (a) Umuahia | c.90 | Yams, maize, cassava | *Acioa barteri* | 1½ | 4–7 | 1½ | 2–2½ | Loam derived from tertiary sands and clays, stumps of fallow carefully preserved. |
| | (b) Alayi | c.90 | Yams, maize, cassava | *Macrolobium* sp. | 1½ | 7 | | | Very loose sandy soil. |
| 9. | Central Congo | >70 | Rice, maize, cassava | Forest | 2–3 | 10–15 | | | |
| | | | | **Moist semi-deciduous and dry forest zone (including humid zone of derived savanna)** | | | | | |
| 10. | West Africa | 60–80 | Maize, cassava | Moist semi-deciduous forest | 2–4 | 6–12 | | | |
| 11. | N. Burma | 50–70 | Hill rice | Grassland and pine forest | | | 5 | 10 | Kochin Hills area at c.6,000 ft. |
| 12. | West Nile, Uganda | 55 | Eleusine, sorghum, simsim, maize | Grass, mainly *Setaria* sp. | 2–3 | 8–15 | 3 | 3 | Refers to 'outside' fields. |
| 13. | Abeokuta, Nigeria | c.50 | | Thicket | | | 2 | 4–5 | Soil derived from tertiary sand; evidence of nitrogen deficiency. |
| 14. | Ilesha, Nigeria | c.50 | | Thicket | 2 | 6–7 | | | Soil derived from granite. |
| 15. | Central Uganda | c.50 | | Elephant grass | 3 | 8 | 1 | 2 | |
| 16. | Ivory Coast | c.50 | | Elephant grass | 3 | 3 | 9 | 6 | |
| 17. | N. Rhodesia | c.50 | | Thicket | 6–12 | 6–12 | | | "Chipya" forest soil. |
| | | | | **Savanna zone** | | | | | |
| 18. | Ivory Coast | 47 | | *Imperata* | 2–3 | 6–10 | 2–3 | 4–6 | |
| 19. | Uganda | c.45 | | *Andropogoneae* | 1 | 2½ | 1 | <2 | |
| 20. | N. Ghana | c.40 | | *Andropogoneae* | 3–4 | 7–10 | | | |
| 21. | French Sudan | 30–40 | | Short bunch grass | 3 | 12–15 | | | |
| 22. | N. Rhodesia | c.45 | | 'Miombo' woodland | 2 | up to 25 | | | Pallid sandy soils. |

References: 1. Freeman, 1955; 2. Popenoe, 1957; 3. Reed, 1951; 4. Waldock, Capstick and Browning, 1951; 5. Hutton, 1921(b); 6. Ypes, 1932; 7. Conklin, 1957; 8. Vine, 1954; 9. Livens, 1949; 10. Irvine, 1934; 11. Leach, 1950; 12. Middleton and Greenland, 1954; 13. Vine, 1954; 14. Vine, 1954; 15. Tothill, 1938; 16. Bergeroo-Campagne, 1956; 17. Allan, 1949; 18. Bergeroo-Campagne, 1956; 19. Tothill, 1938; 20. Goody, 1956; 21. Renard, 1949; 22. Allan, 1949.

followed by only 3 years of fallow for many years, though fertility declines to a very low level at this intensity.

The intensity of cropping which may be achieved without noticeable deterioration in the soils, crops, and fallows is to a considerable extent determined by inherent qualities of the soil, and this can account for considerable variation in native practice over a region. A good rough guide to this inherent quality in the mature latosols is often provided by their content of clay. The heavier soils usually have greater nutrient reserves, a better moisture regime, and more resistance to erosion. Tothill (1938), for example, contrasts the hundred of Ajuluku in Uganda containing light sandy easily erodible soil and barely supporting a population of 174 per sq. m. with the hundred of Kabale, comfortably supporting 435 per sq. m. on a deep red loam.

Such figures as those shown in Table 12 give little impression of the complexity of the fertility pattern in a given region. In examining this matter further we must first make the point that there is no 'ideal' cropping system or ratio of cropping to fallowing that is necessary to maintain fertility. Fertility is a relative term, and within limits, as we have shown in chapter 6, it is possible to crop at varying levels of fertility without any catastrophic consequences to the soil.

The attitude of the shifting cultivator to the soil is quite different from that of a farmer in a less spacious environment. The system of shifting cultivation is not 'designed', like the Norfolk 4-course rotation, to preserve or improve the soil for posterity—that is an attitude to the land which evolves when there is no more room to expand, and personal ownership of the land is established. Nor when there is plenty of land available do the farmers attempt to achieve maximum yields on a given patch, regardless of the effort involved.

In deciding precisely why practices are what they are, we have of course to consider not only soil fertility, but the whole social, historical and environmental setting of the people. But within limits set by custom, the desire to acquire rights over land and so forth, the best general rule to the behaviour of primitive farmers is that they work to get the maximum return for the minimum effort.

The practices dictated by this general rule vary according to the physical environment and according to pressure on the land. In general increasing pressure results in a decrease in the length of the fallow period, but the cropping period is not much altered. An early shift is dictated by a combination of increasing weeds and falling yields, their relative importance varying greatly from area to area, as we have shown in detail in chapter 7. The most important effect of this short cropping period in relation to the stability of the system is that it permits a rapid regeneration of the natural vegetation. Only

in the drier savanna areas is regrowth of the natural vegetation likely to be slow.

The length of the fallow period is broadly determined by pressure of population, but other factors introduce irregularities, among which the settlement pattern of the people is very important. There are two cases to be distinguished. In the first, and generally more primitive, the people are little attached to their dwelling sites, and readily move them every few years to land that carries a mature fallow. In the second the people are more attached to their dwellings, even though these may remain for only ten years or so. This attachment nearly always leads to intensive farming near the settlement and consequent degeneration of the soil, as we shall see later.

In the first case the people have little motive for cropping intensively near their rude settlements, and consequently tend to cultivate land that has been rested for long periods. Some groups, like the Boro of the Amazon forest (Forde, 1934), clear several small, scattered plots; others combine to clear a larger area, progressing like a slow-moving wave through the mature bush. It may be assumed that forest will not be cleared until it has reached a stage where the increased yield to be expected from increased soil fertility is no longer commensurate with the increased labour of clearing more heavily wooded land, a period of ten to twenty years. At the same time the forest fallow must always be long enough to shade out grass weeds, particularly *Imperata* in the Far East. Peoples practising this extensive system of cropping in the forest include the Bantu tribes of the Central Congo Basin, most of the tribes of the Amazon basin, and the Sakai of Pahang, Malaya (Dobby, 1942).

In savanna there is very little difference in the labour of clearing land of different ages. The minimum length of the fallow is then determined by the need for elimination of undesirable weed species. This means a long fallow of 10 years or more in *Imperata*-infested areas, but a shorter period elsewhere. Vast tracts of savanna however, remain uncultivated for much longer periods.

Many of the people in the lands of shifting cultivation today do not so readily move their dwellings. Journeying to and from the farm now becomes an important item in determining the amount of effort involved in farming. If settlements are small and scattered plenty of land is available at no great distance. For example, the long-established villages of the Lamet hill peasants of Indo-China average 56 persons and are surrounded by land which is allowed 12–15 years' forest fallow after one year's rice. All farms are within 1 km. of a settlement (Izikowitz, 1951). But in larger settlements containing hundreds or thousands of people it is usual to find an intensively cropped region near the settlement, with fallows getting longer and longer the further the distance from the home. The reduction in yield near the settlement, on land receiving no form of manure, is compensated by the reduced effort required in getting

to the farm. Hence, for example, we have the pattern of settlement over large parts of the Hausaland plain in Nigeria, which consists of great stretches of little-cropped savanna with islands of settlement surrounded by narrowing irregular circles of increasing intensity of cultivation.

If the settlement is too large for the land within reasonable reach to maintain its needs, the decline in soil fertility eventually becomes so great that the whole or part of the settlement may move to another area. The process is clearly expressed by Haig (1938) as a result of a survey in Uganda: "A proper picture of Buganda agriculture is incomplete without the realization of the extent to which the people move about from one village to another. Probably the chief method by which soil fertility is maintained and restored is not by any system of management or rotation, but by the fact that when the cultivators find their crop yields are diminishing, they leave the village and move to another. In this way whole villages may sometimes lose the bulk of their population within a short period, while other almost uninhabited hills may suddenly become quite populous villages."

Another response to increasing shortage of land around the settlement is the common practice of farmers spending most of the cropping season in a temporary shelter on their farm many miles away from the main village. Thus in northern Yucatan fields range from 2 to 15 miles from the village though in one village in the highland area some fields were 50 miles away (Morley, 1946).

In many areas a more precise relationship between fields near the home and far fields has been established. Those near the home are farmed continuously, or nearly so, and those far from the home on a long-fallow basis. The fertility of the fields near the home is maintained by use of dung and household refuse, and of the far fields by the fallow. In this way relatively stable settlement over quite large areas has been established. Increasing population may however eventually necessitate that some or all of a group move to a new area. When, over a region, the total population was stable it was often possible to accommodate local increases by transfer of land from one group to another. When total population has greatly increased this has not always been possible. The result is that in certain areas fertility of the far fields is not maintained, even at a low level, but continues to decline with each cycle of crop and shortening fallow.

One example of such a situation is described by Lynn (1937) in the North Mamprussi area of northern Ghana. This is a savanna area, receiving 40 in. p.a. rainfall, with light soils of low inherent fertility derived from granite. At the time of Lynn's survey it supported 406,000 people at an average density of 114 per square mile, but at least one third of the area is uninhabited owing to fly-borne diseases, and at present the density in some districts exceeds 300 per square mile. A compound farm averages five acres, though there

are wide variations. 12% of this area receives about 2–5 tons of a mixture of dried dung and refuse each year, and produces on the average about 750 lb. per acre of mixed sorghum and millet. The main effect of the dung is to provide phosphorus, and its quality is such that 1 ton of dung is usually reckoned to be equivalent to 50 lb. of single superphosphate (18% $P_2O_5$). Each year some three acres of non-compound land is also farmed by shifting cultivation, though in the most crowded areas there is little non-compound land left. Little attention is given it beyond seeding and a single hoeing, and it produces only about 300 lb. per acre of sorghum or millet. Both compound and non-compound land gives large responses to nitrogen and phosphate fertilizers (Nye, 1953). The region can just feed itself, and it is further supported by the earnings of the men who migrate each dry season to work on the cocoa farms in the forest region.

A rather similar example has been described by Middleton and Greenland (1954) from the West Nile District of Uganda. In the centre of this District the Lugbara live at a density of 240 to the square mile. Formerly they owned both far fields and fields near the home, both of which were fallowed, and both of which were cultivated to a well recognized rotation. The home fields received only a short fallow, but their fertility was supplemented by the usual additions of dung and household refuse. Increasing population pressure has however created a situation where there is no longer sufficient land for all groups to farm outfields as well as home fields. Many groups (in 1953) were farming only home fields, and the fertility of these was barely being maintained by the traditional practices. The excess population was being supported by very widespread and frequent labour migration to southern Uganda to work on the cotton farms, and the rate of labour migration was closely related to population density. Thus the further decline in fertility which this surplus population would otherwise cause, is to some extent arrested by drawing on the fertility of the richer soils of another area. It is interesting to note that in spite of the loss of outfields the Lugbara still cultivate the same amount of land per head ($\frac{1}{2}$ acre) as in areas of much lower population density and more fertile soils.

An example of the response of shifting cultivation to increasing population pressure in a formerly forested area comes from parts of Onitsha and Owerri Provinces of south-east Nigeria, where under a rainfall of 70–90 in., there are $1\frac{3}{4}$ million people distributed with an average density of 300 per sq. mile (Grove, 1951). In the village of Oko, 3,000 people live at a density of 530 per sq. mile. The individual compound farms of each family are $1\frac{1}{2}$–2 acres. They are planted with oil palms, 13 per acre on the average, and a few other trees, beneath which yams, maize and other intercrops alternate with cocoyam, and rare periods of fallow. In the outside farmland yams sometimes followed by cassava alternate with 3 or 4 years of grass fallow. The compound land is manured with refuse and the dung

of grazing animals. Whereas the yams grown in the compound average 2 to 3 lb. each, those on the outside farmland are only about $\frac{1}{2}$ lb. About one quarter of the food consumed is imported, and again the people are partly supported by remittances from relatives in other parts.

It is apparent from even the relatively few examples quoted here that there is no simple relationship between population pressure and soil fertility. They are closely connected, but there are many other factors which enter the relationship. These include traditional factors, such as pattern and duration of settlement, which are closely linked to the political organization of the tribe or group; and economic factors, which can also influence pattern of settlement, and may, and frequently do, influence cultural practices, through the importance, for example, of a cash crop introduced into the farming system. The effects of labour migration both in relieving pressure on the land and withdrawing menfolk who might otherwise participate in farming operations are also very important.

## Chapter 8

## RETROSPECT AND PROSPECT

A comprehensive assessment of the value of the system of shifting cultivation must be based on a thorough survey of the problems of agricultural development, among which questions of soil fertility form only a part. Nevertheless, the interaction of the system with the soil is supremely important, and because such widely varying judgements have been passed on it, we will give our own conclusions even though they may not do justice to other aspects.

We have to consider shifting cultivation both in the context in which it was evolved, and in the light of present day needs.

The original remote and sparse populations had to win their subsistence from a seemingly limitless forest or savanna. They had no incentive to produce crops for export, no fertilizers and no labouring tools other than the axe and hoe. Often they shifted their settlements as well as their fields, and largely for this reason the system has been strongly condemned, e.g. by F.A.O. (1957). However, as we have seen the methods of shifting cultivation have for long been practised in all three continents by peoples settled in towns, villages or hamlets which have endured for tens or even hundreds of years. Many of these people, like the Ashantis, have attained a high level of organization and culture. Against such a background we may fairly ask whether the system gives a satisfactory

return for the effort expended. We may also ask whether it squanders the resources of the land for future generations.

In the forest there is the clear answer to the first of these questions that so far as we know the system is the best that could have been devised; for as we have shown, the labour of clearing, planting and weeding in relation to the size of the harvest is low. It is notable that in the forests of the eastern United States the European settlers of the seventeenth century adopted the shifting cultivation methods of the Indians and continued to use them for two and a half centuries. The consequences of using the techniques of regions with gentler rainfall, such as rooting and stumping followed by ploughing and row cropping, which were adopted, when pressure on the land became more acute, are now apparent in widespread gulleying and the disappearance of much of the former top soil.

We may therefore ask whether it is true that the system of shifting cultivation, even if it provides a satisfactory livelihood, squanders the resources of the land. The main objections which are raised are that the system destroys the forest, causes loss of organic matter by burning, destroys valuable humus and leads to excessive loss of nutrients by leaching.

Without some destruction of forest no agriculture would be possible. Harm is done only if the forest is wanted for other purposes, such as production of timber. The extra surface run-off and possible climatic influences associated with the small scattered peasant plots are negligible. The substance to the argument about losses of organic matter and humus disappears when the system maintains humus at a satisfactory level, as it can do with sufficiently long fallow and short cropping periods. Some mineralization of humus is inevitable on cropping, but traditional methods involving little disturbance to the soil and good shade prevent the rate becoming excessive. Large quantities of nutrients are certainly leached out of the topsoil during the cropping period, but we do not know as yet to what extent they are leached beyond the root zone of the fallow. As we have shown the point largely depends on the fate of the nitrate ion, which is leached in large amounts from the top soil yet is found only in traces in the streams. These largely drain fallow land, so whether the nitrate is lost from the solum of cultivated land remains uncertain, and until the answer is known we must suspend judgement.

When intensification of cropping leads to the formation of savannas dominated by *Imperata cylindrica* or the high-grass Andropogoneae there is no doubt that the natural resources of the land have been permanently impaired. Whether replacement of the forest by elephant-grass savanna represents a deterioration is not yet established.

In savanna there is far less to be said in the favour of the system. Though the return from the labour expended is less than in forest, in the adverse environment of the savanna regions the systems of

cultivation and cropping are in general well adapted to produce the means of subsistence with the minimum of labour. Detailed studies of tribes farming the savanna have revealed their keen awareness of local variations of soil and vegetation to which are adjusted the finer details of cultivation practice and varieties of crops grown. Nevertheless the methods practised are wasteful of resources since they are directed entirely to the needs of the moment, and do little to protect the soil. Most of the objections to shifting cultivation in the savanna stem from the practice of annual burning, which checks the growth of shrubs and trees, and encourages erosion on all but gentle slopes. Erosion is also promoted by the methods of cultivation as already described. But even without these practices, the natural grass savanna fallow is a very poor means of restoring the fertility of the land. It stores only small amounts of nutrients, and it maintains a chronic shortage of available nitrogen, which checks the growth of the grasses themselves, the associated woody species, and the subsequent crops. The increase of humus in the top inches of soil and the maximum level possible are considerably less than those under forest, and the physical condition is poorer. Nothing but loss is the result of the conversion of forest to high-grass savanna dominated by Andropogoneae.

We shall now consider briefly whether the system of shifting cultivation can be adapted to meet the present day need to produce more food from the land and raise the general living standards of the people or whether it must be discarded entirely.

In considering this question one inevitably wonders why tropical forest soils cannot be made to produce high yields of food by the same methods that have proved so effective in temperate regions.

The highly productive agriculture of present day Europe has only slowly evolved from shifting cultivation. When irregular cropping settled down to the open field system, fertility was maintained at a low level by a year of fallow after one or two years of crops, and by the limited amount of manure that reached the fields from animals grazing the common land beyond. The fallow was only finally abandoned with the introduction of root crops as winter fodder, leading to more cattle and more manure. Today fertility is maintained by a reversion to a fallow system—though with greatly improved fallows—called ley farming, by imports of feeding stuffs, and above all by inorganic fertilizers.

There are a number of purely technical reasons why these methods are difficult to introduce in tropical forest regions, quite apart from the economic and social reasons, and they lead many to think that special solutions must be found.

The clearing of forest for the plough, which involves complete rooting and stumping, is enormously costly. Even in forest land degraded to thicket the roots and stumps are far more formidable than the top growth suggests. Mechanized cultivation does of course destroy the whole basis of the natural fallow system, and if fertility

is to be restored by any sort of fallow it must be deliberately planted. Another obstacle to mechanization, peculiar to the tropics, is termite mounds. In the central Congo basin, for example, the mounds may contain as much as 1,800 cu. m. of earth per hectare—effectively about 8 in. depth when spread (Culot and Meyer, 1959). Much of this earth may consist of poor subsoil, and precautions have to be taken to avoid sterile patches on the sites of the mounds.

The rainfall of temperate Europe is mild and it is usually possible to leave the land unprotected without serious erosion. In the humid tropics the intense rainfall renders permanent cropping with a succession of well fertilized annual crops extremely hazardous on many soils, even when erosion defences have been installed.

The earliest European farmers were cattle owners. There are few cattle in the tropical forest regions and they are unthrifty. There is no tradition among the native peoples of caring for animals. Improvement of indigenous breeds in Africa is restricted by trypanosomiasis, prevalent throughout the forest and moist savanna regions.

Fertilizers are expensive in relation to the value of the increased yields of subsistence crops. Under present systems of farming they can be profitably used only at low rates of application on heavily farmed areas where the fallow has been reduced to a few years only.

Eventually the demand for food and livestock products by the growing towns, and availability of cheaper fertilizers, may bring to the forest regions continuous cropping maintained by large applications of fertilizer, and pastures grazed by much improved animals, but at present these lie well into the future. Possibly in an ideally planned economy the forest lands would be left to produce timber or the perennial cash crops like cocoa and rubber for which they are so well suited, and would import their subsistence requirements from the savanna regions or even further afield. However, in so far as subsistence crops continue to be grown on upland forest soils some form of rotation involving natural or planted fallows seems likely to persist in the forest regions for very many years.

The improvement of the natural fallow is a specifically tropical solution to the problem which has attracted much attention. There is however no evidence yet that a planted fallow will restore the fertility of a forest soil any faster than the natural woody fallow. It is the fastest growing species in the natural fallow that win the race for light, and the possibilities of finding very much more vigorous species are not hopeful. In particular we must emphasize that the nitrogen status maintained beneath a forest fallow is good, and there is no reason to think that long-term leguminous fallows would offer any advantage. Short-term leguminous fallows or green manures have the disadvantage of leaving the soil exposed while they are being established. Though no rigorous comparisons between green manuring and natural fallowing have been made, green manuring was formerly widely advocated in the semi-deciduous forest region of Nigeria (Faulkner and Mackie, 1933); yet no

Plate 1

A typical food farm in semi-deciduous forest.
The cassava and plantain have been established 18 months, and are intermixed with forest regrowth. In background, mature trees with secondary growth about 15 years old.

Plate 2

The beginning of cropping—first year, January, middle of the dry season.
The forest has been cut, and will be burned when dry. The largest trees have been left standing.

Plate 3

First year, May, one month after the beginning of the rains.
Maize is interplanted with cocoyam (broad arrow-head leaf) and cassava (five-fingered leaf). Some forest litter and a few weeds help to protect the soil.

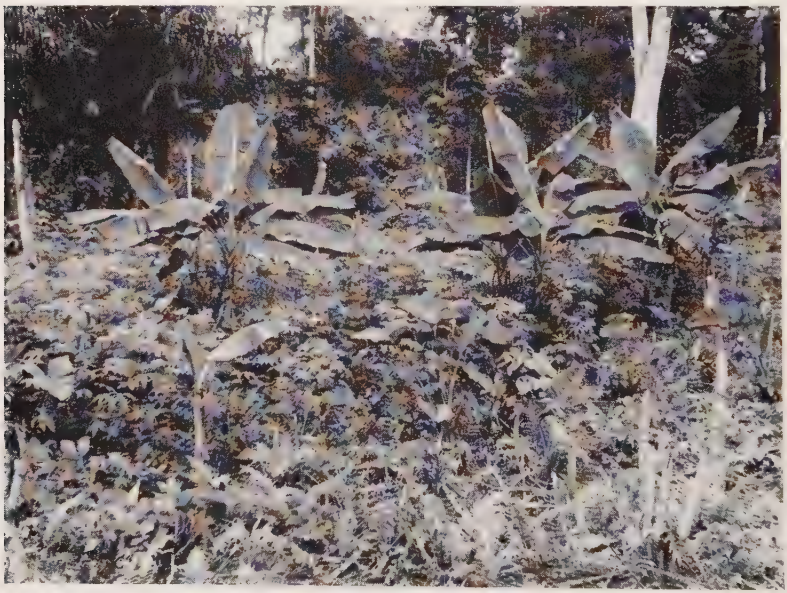

Plate 4

First year, December, the end of the rains.
Maize has been harvested. Cassava, cocoyam and plantain form a close canopy above a ground cover of weeds.

Plate 5

Second year, September.
A magnificent stand of plantain, with cocoyam and a little late-planted cassava. The first planting of cassava was destroyed by cane rats.

Plate 6

Third year, June.
The farm is 'going back to bush'. The quick-growing Umbrella Tree (*Musanga cecropioides*) and other trees are permitted to overshade the crops, which may be harvested spasmodically for another year or so.

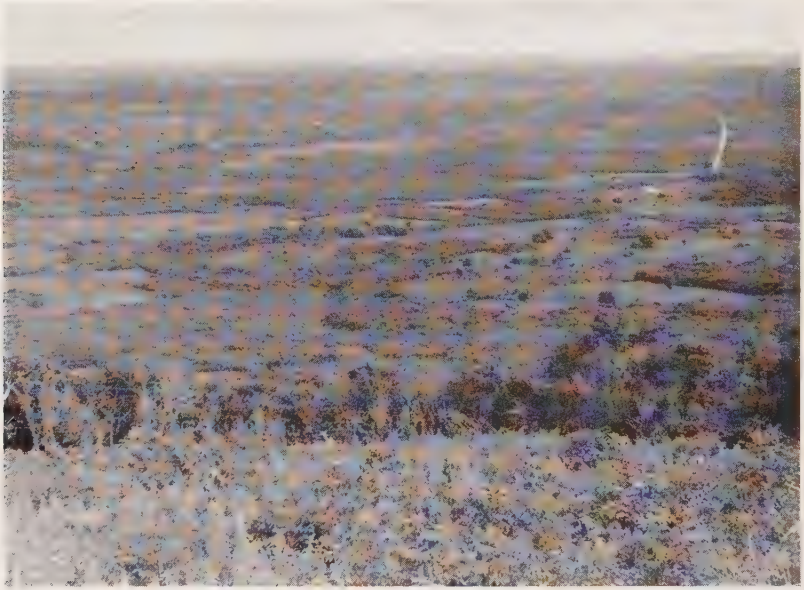

Plate 7

The pattern of shifting cultivation. Below Aburi, Ghana.
Field patches of semi-deciduous thicket in all stages of cropping and regeneration. Cropping lasts about two years and fallowing up to ten years. Land in first year of fallow in the foreground.

Plate 8

Fixed settlement amid shifting cultivation. Enclosed house and garden. Middle Guinea.
Settlements are often surrounded by a well manured garden planted with a wide assortment of crops. Here the ground crops are sweet potato and cocoyam; with a pepper bush (foreground), cotton (near house to left), and Hibiscus fibre (right) also visible.

Plate 9

Cultivation of Slopes. Akwapim Hills, Ghana.

Plate 10

Cultivation of Slopes. Upland rice. Middle Guinea.
Steep slopes do not deter a farmer who uses only a cutlass or hoe. Drainage is good and the soil usually fertile—before it erodes away.

Plate 11

Mature secondary forest. Kade, Ghana.

The dense secondary growth is about 40 years old. The tallest trees were left standing when the forest was last cleared. Data for this forest are given in Tables 2 and 6.

Plate 12

Elephant-grass savanna. Adaiso, Ghana.

This vigorous grass can attain 15 to 20 feet. This savanna was derived from moist semi-deciduous forest.

Plate 13

High-grass tree savanna. Senchi, Ghana.
*Terminalia* spp. are prominent among the fire-hardy trees and shrubs, and *Hyparrhenia* and *Andropogon* spp. among the grasses.

Plate 14

*Imperata cylindrica* var. *africana*. Legon, Ghana.
The sharp pointed leaves (hence 'spear grass') and white feathery heads are visible. The height is 3 ft. The Asian form, var. *major*, grows taller and denser. *Andropogon gayanus*, 8 ft. high, is in the background.

DEVELOPMENT OF SAVANNA BY FIRE (Plates 15–16)
Protection plots. Near Bouake, Ivory Coast, 1959.

Plate 15

Complete fire protection in background, late burning in foreground.

Plate 16

Early burning in background, late burning in foreground.
The plots were established in 1937. With complete protection grasses have almost disappeared, and fire-sensitive forest species are re-established. With burning early in the dry season, giving a mild fire, the fire-hardy savanna trees have closed up. With burning late in the dry season, giving a hot fire, shrubs and trees are sparse.

farmer has adopted the practice, in preference to the bush fallow. If fallow growth on very acid or worked out soils is restricted by shortage of nitrogen a leguminous fallow which bore active nodules would be expected to have some advantage. Leguminous green manures have however made poor growth on the acid soils of south-eastern Nigeria.

There is a wide range in the nutrient composition of the individual species which make up the forest fallow (Nye, 1959), and there is the possibility that certain of these could be selected because they promoted a rapid accumulation of phosphorus or potassium in the top soil or in the fallow.

As we have seen it is important that the fallow should establish itself rapidly. If the establishment of the natural fallow is slowed by over-cropping or invasion of grasses there is benefit in deliberately planting quick growing trees. Pelzer (1948) gives examples of a number of peoples who adopt this practice in different parts of south-eastern Asia, thus checking the invasion of *Imperata cylindrica*. In the worn-out soils of south-eastern Nigeria the Rosaceous shrub *Acioa barteri* is deliberately planted by some farmers. There is nothing unusual about its composition (see Table 2), but it is very deep rooted and thrives under poor conditions (Vine, 1956*b*).

Planting of fallows that can be put to economic use is also practised. The 'taungya' system of establishing pure stands of timber species by clearing for food crops and planting the valuable trees amongst them has been known to foresters for over a century. The use of a semi-perennial crop like bananas as a fallow has been advocated (Hendrickx and Hendrickx, 1949; Nye, 1957). Vigorous hygrophilous grasses such as elephant grass or guinea grass may be planted and either grazed, soiled or conserved in those parts of the forest where livestock can be kept.

Mechanized clearing of bush fallows has been advocated. Charter (1955) has suggested that woody fallows that coppice freely should be planted in rows and at the time of cropping they could be cut with tractor operated circular knives, the crowns being burnt on the spot and the stems used for firewood.

One of the greatest barriers to these technically feasible modifications is the land tenure system. The ownership or right of use of a tract of land usually belongs to a tribal group. An individual farmer belonging to the group has the right to use part of the tribal land for cropping, but his interest in his plot may cease when it is abandoned to the natural fallow. He has therefore no incentive to improve it.

Attempts have been made in the Belgian Congo to combine the merits of the natural forest fallow with a system of individual ownership. In the "corridor system" the land is divided into parallel belts 100 metres wide. Successive corridors represent different phases of the crop and fallow rotation. Each family is given a holding which runs in a strip at right angles to the corridors, and thus includes land

in all stages of crop and fallow. The different modifications of this scheme are described by de Coene (1956). The institution of such a system does of course require a strong measure of control over the land and the population.

In the savanna region the problems of adapting the system of shifting cultivation to present day needs call for rather different solutions, mainly due to the long dry season, the more favourable environment for cattle, and the greater ease of clearing for the plough. This is not the place for a comprehensive review of the development of the savanna regions, and we can only indicate briefly the part which the methods of shifting cultivation are likely to play in this fascinating process.

The most widely practised recommendation in the high-grass savanna is the early burning of the grasses. Burning at the beginning of the dry season does less damage to the woody species, and it encourages a fresh growth of grass, which protects the soil at the beginning of the following rainy season. A late burn is very fierce, and leaves the soil exposed to the early rains.

It is extremely difficult to enforce a total ban on burning, and attempts to do so often result in catastrophic late burns.

This policy of early burning to encourage woody species must be carefully distinguished from the necessary and deliberate burning practised in drier savannas to eliminate undesirable shrubs from grazing land (see Guilloteau, 1958, for a recent review).

Deliberate planting of improved fallows is adopted to a limited extent. In the elephant-grass region of Uganda this grass is deliberately planted at the end of the cropping season rather than allowed to establish itself gradually over the course of some years. In the high-grass areas severely short of available nitrogen, a semi-perennial leguminous fallow which will survive the dry season, such as *Cajanus cajan* or *Tephrosia* spp. is certainly more effective than the natural savanna fallow (Nye, 1958; Stephens, 1960*b*), though whether the extra trouble is sufficiently rewarding to the farmer has yet to be proved.

Green manures, such as *Crotalaria* spp., were formerly extensively used by European maize growers in Southern Rhodesia, mainly as a source of available nitrogen. They have never been accepted by the native farmers partly because they have as a rule no plough to turn them in, and the native farmer who does have a plough finds it more profitable to use it only on land growing food. The idea that ploughing in green manures will reduce erosion is now thoroughly discredited. In fact, Hudson and Jackson (1959) find that in Southern Rhodesia a rotation of maize and green manure causes greater losses than continuous maize; and Fournier (1959), a French authority reviewing the subject, concludes that 'the researches carried out a few years ago in Africa on green manures show that their burial in the ground only serves to increase the cultivation

output which ensues. On the other hand they only increase slightly the resistance of the soil to the action of erosion by water.'

The possibilities of introducing fallows of economic value are severely limited by the severity of the dry season. Farmers do however tend to preserve trees of economic value such as *Butyrospermum parkii*, *Parkia clappertonia* and *Acacia albida* in their fields, and these effect some very localized improvement in the soil.

Much the most promising prospect of utilizing fallow land is for the feeding of livestock, in the first place as grazing, and later, with increased knowledge, as hay or silage. While this may lead to a system of alternate husbandry, the present tendency is in the direction of permanently cropped fields run in conjunction with outlying grazing land. As we have seen, a system of permanent cropping on land surrounding the compound, combined with shifting cultivation on the more remote non-compound land has long been practised by tribes who were in other respects extremely backward. The compound land was maintained at a moderate level of fertility with a limited amount of dung and the refuse of the household. Under European influence this system has been developed by introducing the bullock drawn plough, and encouraging farmers to keep more animals and to make more and better quality manure for their compound land. The pattern emerging, for example in Northern Nigeria and Ghana, and in Southern Rhodesia, is of permanently cropped land protected from erosion by contour banks and contour ridging, and maintained in fertility by manure provided largely from animals fed on the natural grazing land beyond. The cropping of the non-compound land by the methods of shifting cultivation disappears and the transition to permanent cultivation is complete. The further great advantage of this system is that the farmer can own all his land. He is encouraged to improve its fertility by buying fertilizers, and he has a capital asset to form the basis for agricultural credit.

For any form of intensified production in the savanna, whether by shifting cultivation or by permanent cropping, fertilizers, especially nitrogen and phosphate, are essential. Without them the vicious circle of poor fallows leading to poor crops cannot be broken. Even in a thorough-going mixed farming system there is rarely enough grazing land available to provide enough manure for the cropped land. It may prove that not only the cropped land but the grazing land should be fertilized.

Fertilizers are only recently coming into use in the savanna areas. Their cost is high, and under current native practice of wide spacing, with varieties adapted to conditions of low fertility, the increase in yield, while often large when compared with the current yields, is insufficient to pay for more than a low rate of application. As communications improve and the costs of fertilizers are lowered relative to the value of the produce, and as techniques of cropping and varieties of crops are introduced that respond better to increased

soil fertility, it seems likely that the methods of shifting cultivation, relying on natural fallows to restore fertility, will gradually disappear from the savanna regions.

Fears are expressed that permanent cropping with a rotation will lead to serious erosion on the more erodible savanna soils, which it will not be possible to check with mere mechanical methods of erosion protection. For this reason ley farming is advocated; and it is possible that the methods of shifting cultivation in this much modified form will find a place in the future. Quite apart from the skilled management required, the case for ley farming is not yet proved on technical grounds. It is generally accepted that the most effective way of checking erosion is to keep a good cover on the land, and this means early planted vigorous crops. As we have already indicated in discussing the constitution of the soil, there is still doubt whether resting the land under grass, especially on the more erodible sandy soils, goes very far towards promoting a resistance to erosion when the land is again cropped. Naturally, a period of rest under grass reduces the annual rate of erosion, but it is not yet clear to what extent it reduces the loss for each annual crop grown. In drier areas the perennial grasses may also deplete reserves of subsoil water on which the annual crops depend. To establish the future place of the ley under tropical conditions what is needed above all at present is critical experiment that will convert what is so often mere assertion into established fact.

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